JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

Project

Novel semiconductor detectors for fundamental and applied research

Report and Proposal for prolongation

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Abstract

Since 2006, the DLNP has been researching and developing semiconductor detectors for fundamental and applied research on the basis of a new material - chromium-compensated gallium arsenide (GaAs:Cr), produced at the Laboratory of Functional Electronics of Tomsk State University. Over the years, including the last three years of the proposed Project, more than a hundred prototypes of GaAs:Cr sensors have been developed and manufactured for semiconductor detectors used in a wide range of fields of science and technology, from high-energy physics to computed tomography; infrastructure was created to measure characteristics and study properties of semiconductor materials and detectors based on them; scientific contacts were established with the world centers conducting similar research, and a number of joint research projects were carried out.

The experience of production and operation of semiconductor detectors based on modified gallium arsenide accumulated in the DLNP allows to proceed both in solving more complicated problems in the chosen fields of research and in searching for new applications for such detectors.

In the course of further development of the Project, it is planned to conduct new scientific and methodological research, in particular, to search for ways to increase the radiation hardness of gallium arsenide based detectors, to identify particles by cluster type in hybrid pixel detectors, to develop pixel detectors for experiments with hypernuclei and relativistic ions on the Nuclotron. It is also planned to improve the existing research infrastructure at the DLNP, including creation of a station for deep level relaxation spectroscopy (DLTS) and mastering of this technique, creation of another microtomograph with a fixed detector and a rotating sample table capable of achieving a spatial resolution of 5-7 μm due to geometric magnification, creation of a full-featured readout electronics unit for acquisition of data from the Medipix-4 chip. The development of software for modeling and reconstruction of tomograms will continue, with emphasis on improving the quality of images, the use of fast algorithms for processing large volumes of tomographic data and new hardware capabilities.

In the field of applied research with the use of methods of spectral microtomography we will continue to study, in particular, the possibility of predicting the development of vascular arteriosclerosis based on measurements of the fine structure of calcium deposits in the walls of atherosclerotically affected carotid arteries and aortic aneurysms, the identification of adipose tissue in animals by combining information on the density and energy dependence of the linear attenuation coefficient, the possibility of isolating roentgen contrast substances in the body for the delivery of drugs to the needed tissue

by using radiopaque markers, the identification of mineral phases in ore and mineral raw materials. The possibility of creating microdosimetric probes based on Timepix detectors for measuring the equivalent dose of irradiation will also be studied.

The requested amount of funding for the implementation of the Project is 450 thousand US dollars for three years.

Chapter 1

Project goals

The success of a scientific experiment crucially depends on the equipment that it uses. To a large extent, the progress in understanding of the physical picture of the world that has occurred over the last century has been provided by technological achievements that allowed creation of more advanced experimental facilities and improvement of data processing methods. Scientific and methodological research to develop new types of detectors is a necessary condition for the further development of experimental nuclear physics and elementary particle physics. Of course, such studies are successfully carried out during the preparation of a particular experiment, as each new physical problem poses its own requirements on the experimental setup. However, such an approach aimed at the near term, often hinders the development of completely new, and not yet quite established, methods of detecting particles tailored to the needs of future experiments.

Preparation of accelerator experiments of the new generation (ILC[1], CLIC[2], HL-LHC[3]) requires the development of new types of detectors, capable of working under high load and at the same time providing the required accuracy and reliability of particles registration. Creating new types of detectors of elementary particles is important not only for high energy physics. The future of biology, materials science, geophysics and medicine is closely associated with investigations conducted on synchrotron radiation and X-rays sources, as well as other nuclear physics methods. In the next decade the beginning of studies at XFEL[4] complex is expected alongside with the launch of new synchrotron sources and ELI[5] centers being constructed in the JINR member states in the framework of ESFRI[6]. For the experiments at these facilities data acquisition systems, primarily image detectors,

[1]International Linear Collider [1].
[2]Compact Linear Collider [2].
[3]High Luminosity Large Hadron Collider [3].
[4]European X-ray Free Electron Laser [4].
[5]Extreme Light Infrastructure [5].
[6]European Strategy Forum on Research Infrastructures [6].

with high spacial and energy resolution are required. The development of such detectors nowadays is largely based on the experience gained in nuclear physics and high energy physics.

Joint Institute for Nuclear Research and, in particular, Laboratory of Nuclear Problems have a rich history of methodical research and development of a wide variety of detectors. Moreover, we can safely say that the Laboratory owes its most striking physical results to the scientific and methodical studies conducted beforehand. This statement applies not only to the experiments carried out at JINR, but, to a less degree, also to the visiting experiments at accelerators of other centers. The proposed Project aims to create in the DLNP a research infrastructure for conducting scientific and methodical studies on the development of new types of semiconductor detectors for accelerators experiments. Since these detectors can be successfully used in applied research in other fields of science, an important component of the proposed Project is to create a working scheme for joint interdisciplinary applied studies and for implementation of the results in innovative fields of the economy of the member states.

For a long time semiconductor detectors have been used as sensitive elements of coordinate and calorimeter subsystems of various experimental installations that combine high readout speed with high spatial and energy resolution. However, the requirements for the planned detectors of the next generation of experiments (for ILC, CLIC, HL-LHC, the muon collider, etc.) are considerably higher than the characteristics of semiconductor detectors achieved today. To fulfill those requirements additional research and development in the field of semiconductor detectors is needed. The list of necessary improvements includes higher readout speed, higher degree of segmentation and, more importantly, a cheaper price tag, since we are talking about large installations with hundreds or thousands of individual detecting elements. However, in contrast to the LEP[7], Tevatron and LHC[8] experiments, on the top of the requirement list is radiation hardness because of much longer life cycles and much higher luminosities of the planned future accelerators in comparison to the existing accelerator complexes.

Modernization of the LHC experiments for the Phase-2 stage and detector projects for the ILC experiments impose the dose of ionizing radiation up to 1 MGy and non-ionizing radiation fluence up to $2 \cdot 10^{16}$ MeV·n/cm^2 [7]. All existing silicon detectors become inoperative after accumulation of a dose smaller by an order of magnitude. The only known method for operation of silicon detectors under such radiation load is reducing of the operating temperature down to several tens of degrees. However, this method significantly complicates the design of the detector and raises intractable requirements on the detector

[7]Large Electron-Positron collider

[8]Large Hadron Collider

heat output. The last requirement is particularly important since the high load on the detector implies a complex trigger system that require rather complicated signal processing directly in the detector, including time measurements, clusters recognition and measurement of correlations between signals in adjacent pixels. The only alternative to frequent, time-consuming and costly replacement of detecting elements damaged by radiation in the current day installations is development of a new generation of radiation-resistant detectors, based on modern technological advances and the use of new materials.

Developments in the field of semiconductor detectors is largely determined by technological advances in industry. Nowadays, practically none of the research institutes grows silicon crystals or manufactures readout chips for its needs in high-energy physics because it is much easier and cheaper to do at the enterprises of the microelectronic industry. In most research centers for high-energy physics the emphasis shifted from the actual production of detectors to making specifications for detectors, to design and assembly of prototypes or sometimes small-scale batches of detectors from commercially produced elements. The most important stage in the development cycle of new detectors is the study of their characteristics, which provides feedback to the manufacturer of sensitive elements. The study of detector characteristics includes both the control of correspondence of the basic detector properties to its specifications and direct evaluation of the sensor detecting properties. The key tests for new detectors are tests on beams of different elementary particles that allow studies of the detector properties in conditions close to operational. Regarding the evaluation of detector radiation hardness, these tests are the most important. In this respect JINR has a great advantage, because it possesses a large number of installations that allow testing of detectors in beams of different particles, from protons and neutrons to heavy ions. The close scientific relations with almost all world centers of high-energy physics allow, if necessary, to carry out such beam tests at any accelerator in the world.

Development of semiconductor detectors based on a new radiation-resistant material - modified gallium arsenide produced by Tomsk State University (TSU) - has been conducted in the LNP since 2006. In the course of this development scientific relations with the world's centers performing similar studies were established, a number of joint research projects with TSU to create a sensor with the desired properties were carried out, considerable experience in the production and operation of such detectors (in pad and pixel geometry) was accumulated, the detector characteristics were measured. The obtained experience allows to move to more complicated tasks and to pursue developments in several directions simultaneously. The following tasks form the basis of the proposed Project:

1. Development of the existing scientific and technical groundwork for design and development of semiconductor radiation-resistant detectors based on new materials

and hybrid pixel detectors with high resolution for accelerator experiments. In the future - the development of some of the necessary, but currently lacking, facilities in the LNP: for mechanical and chemical processing of semiconductors, for assembly of pixel detectors and for design of readout electronics.

2. Improvement of the existing and development of new testing stations for measuring properties of detectors produced at JINR and at laboratories of JINR member states, coupled with beam tests at the specialized JINR facilities.

3. Joint scientific work in collaboration with research groups from other institutes in feasibility studies of application of the newly developed detectors in other areas of science and technology (primarily in the fields of medicine and geology), in particular, applications for the MARS microtomograph that uses the new sensors with modern readout electronics based on the Medipix chip.

In the following chapters the main results obtained during the implementation of the 2015-2017 Project for each of the tasks are presented alongside with the proposed work plan for 2018-2020.

Chapter 2

Investigations of semiconductor detectors for nuclear physics and particle physics

The basis of operation of semiconductor detectors is the formation of non-equilibrium charge carriers (electrons and holes) during passage of an ionizing particle. If an electric field is applied to the semiconductor the drift of the non-equilibrium charge carriers generates a current pulse in the detector circuit, which can be amplified and recorded. Silicon and germanium are traditionally used for the production of semiconductor detectors, with the latter mainly being used in precision spectroscopy. Of great interest are other semiconductor materials suitable for making detectors, such as CVD-diamond, silicon carbide, gallium nitride and gallium arsenide.

The latter material is especially interesting because it has long been used successfully in the microelectronic industry in manufacturing of devices and integrated circuits for ultra-high-speed and microwave electronics. In this regard, there exist in the world industrial technologies for the production of gallium arsenide and its properties have been thoroughly studied. In world practice, semi-insulating gallium arsenide (LEC-GaAs) is commonly used. However, this type of gallium arsenide has significant drawbacks that limit its use as a material for the production of particle detectors. The main problem is the impossibility of creating a detector material with a low content of impurities. As a result, the maximum depth of penetration of the electric field in the sample is 200 - 250 μm, which limits the thickness of the sensitive layer of LEC SI-GaAs structures. Consequently, despite numerous attempts in the world, until recently it has not been possible to create semiconductor detectors of ionizing radiation of good quality on the basis of semi-insulating gallium arsenide.

Progress in recent years in the creation of such detector material is associated with the work of the Tomsk scientific school under the leadership of O. P. Tolbanov, a professor at Tomsk State University. The technology for compensation of n-type conductivity in LEC

GaAs layers in the process of thermal diffusion of deep acceptor impurity of chromium (GaAs:Cr) was developed. The experimental values of the resistivity of such structures are measured to be about 10^9 Ohm·cm, which is by more than an order of magnitude greater than the resistance of structures based on LEC SI-GaAs. This implies the transition from barrier-type structures to structures of resistive type. Ohmic contacts can be formed to such structures that allows for a uniform distribution of the electric field strength over the entire thickness of the detector. To date, samples of chromium compensated gallium arsenide with a thickness of the sensitive layer up to 1 mm have been obtained at TSU [12].

One of the most complex technical issues in creating a semiconductor detector is readout of the signal. If for a pad or micro-strip detector the readout can be made relatively easily, for a pixel detector the signal readout is a much more complex problem. When the size of an individual pixel is reduced to hundreds or tens of microns and the total number of pixels reaches thousands or tens of thousands, there is no other ways besides developing of a specialized readout chip containing the required number of channels of electronics. Thus, we obtain a hybrid pixel detectors consisting of a sensitive layer (sensor) made of a single crystal semiconductor and a readout chip, interconnected by bump-bonding (Figure 1).

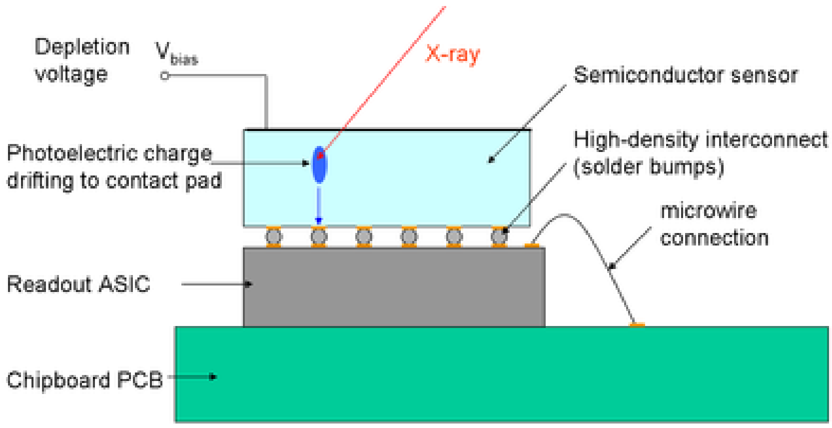


Figure 1: Typical scheme of a hybrid pixel detector.

The conventional electronics used to readout signals from pixel detectors amplify the electrical signal first and then integrate it to determine the amount of the collected charge. It implies that the intrinsic noise of the sensor is inevitably added to the signal, that leads to a deterioration in image quality and a decrease in the energy resolution. However, over the past 10 years advances in microelectronics have made it possible to implement a fundamentally new approach, in which the spectrometric circuit is assembled directly in a single pixel. It allows to carry out not only amplification, but also amplitude discrimination and digitization of the signal in the pixel. The high readout speed of such circuits makes possible to be performed these operations independently for each particle. The output signal in this way is digital, namely, the number of particles with energy above a predetermined threshold set by the discriminator, instead of an analog signal proportional to the collected charge. This approach has been called the single photon counting mode, since it was first implemented for photodetectors.

The development of such readout microcircuits is carried out by three groups: in PSI (Switzerland, PILATUS [14] family of chips), CPPM-IN2P3 (France, XPAD [15] family of chips) and MEDIPIX collaboration (CERN, Medipix2, Timepix, Medipix3 [16] chips). In terms of their characteristics (the size and number of pixels, capabilities of readout electronics), the Medipix family of chips outperform the analogues developed by the other two groups.

2.1 Main results in 2015-2017

2.1.1 Investigation of radiation hardness of detectors based on gallium arsenide

The radiation hardness of LEC gallium arsenide has been studied some time ago by the RD8 experiment at CERN [9]. It has been shown that detectors made of uncompensated gallium arsenide can withstand a fluence of $3 \cdot 10^{14}$ protons, $2 \cdot 10^{14}$ pions and $6 \cdot 10^{14}$ neutrons per cm^2. For compensated semi-insulating gallium arsenide a similar radiation hardness was determined, and also it was shown that the dose of 100 kGy accumulated during irradiation by photons with energy of 660 keV leads only to a slight deterioration of the detection properties [10]. Studies conducted by irradiating GaAs detectors with 1.17 and 1.33 MeV gamma rays from a ^{60}Co radioactive source did not show significant radiation damage up to the accumulated dose of 1 MGy [11]. Radiation tests of GaAs:Cr pad detectors made at JINR, which were carried out within the framework of the FCAL collaboration on an electron beam with an energy of 8.5-10 MeV on the S-DALINAC accelerator in Darmstadt, showed that the detectors remain operational until the accumulated dose of 1.5 MGy [13]. Although it was shown that the compensated gallium arsenide is quite a promising material for high radiation resistant detectors, until recently systematic measurements of radiation hardness of GaAs:Cr detectors in comparison with silicon detectors were absent, as well as studies with neutron beams. In addition, studies of radiation hardness of barrier $\pi\nu$-structures on electron beams have never been carried out at all.

In the framework of this Project, in the autumn of 2016, systematic tests of radiation hardness of 2 types of gallium arsenide pad detectors (barrier $\pi\nu$-structures and highly

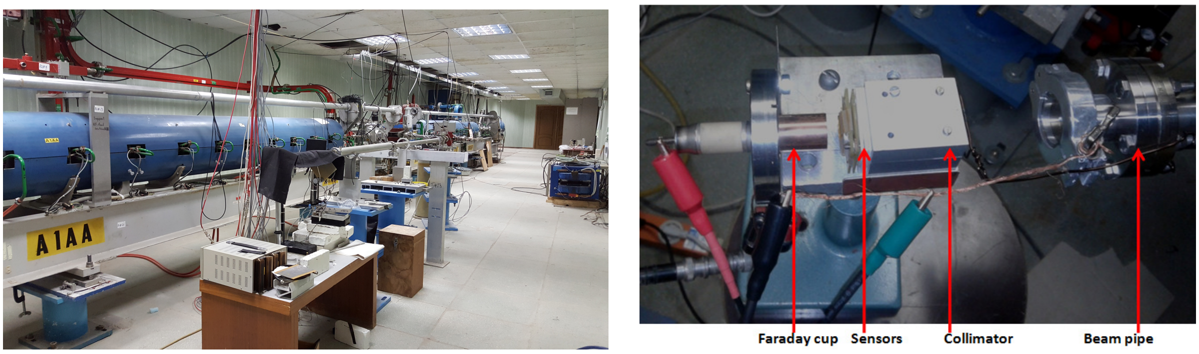


Figure 2: The output beam-line of the Linac-200 accelerator and the setup for irradiating pad sensors.

resistive structures) and n-type silicon detectors on an electron beam with an energy of 20 MeV were conducted. The tests were carried out at the LINAC-200 accelerator at JINR (Figure 2). The detectors with an area of 5 mm $\times$ 5 mm were irradiated in steps of dose from 50 kGy to 200 kGy until a total absorbed dose of 1.5 MGy was achieved. After each step, the current-voltage characteristic and the charge collection efficiency at room temperature were measured.

As a result of the tests, it was shown that the radiation damage affects the performance of the silicon and gallium arsenide detectors in different ways. Silicon is characterized by a rapid increase in the dark current, up to 4 orders of magnitude when irradiated with a dose of 1.5 MGy. This makes impossible usage of silicon detectors without cooling under irradiation with a dose of more than 0.5 MGy, although the charge collection efficiency remains constantly high. As for GaAs:Cr, the dark current increases moderately, three times for resistive material and 4-5 times for barrier structures. However, gallium arsenide is characterized by a decrease in the efficiency of charge collection. It should be noted that the charge collection efficiency in GaAs:Cr decreases sharply (by a factor of 5) when irradiated with a dose of 0.5 MGy, and then continues to decrease slowly with a further increase in dose, remaining at a level of 10% at a dose of 1.5 MGy, which is quite sufficient for the detector to be operational. The curves of the current-voltage characteristics, charge collection efficiency, and examples of spectra are shown in Figure 3,4,5, respectively.

Similar results were obtained by irradiation with neutrons in the beams of the IBR-2M reactor (Figure6). The tests were carried out in November 2016 for two types of detectors based on GaAs:Cr and one n-type silicon detector, with three values of fluence: $5.5 \cdot 10^{11}$, $2 \cdot 10^{12}$, and $4.5 \cdot 10^{13}$ n/cm^2

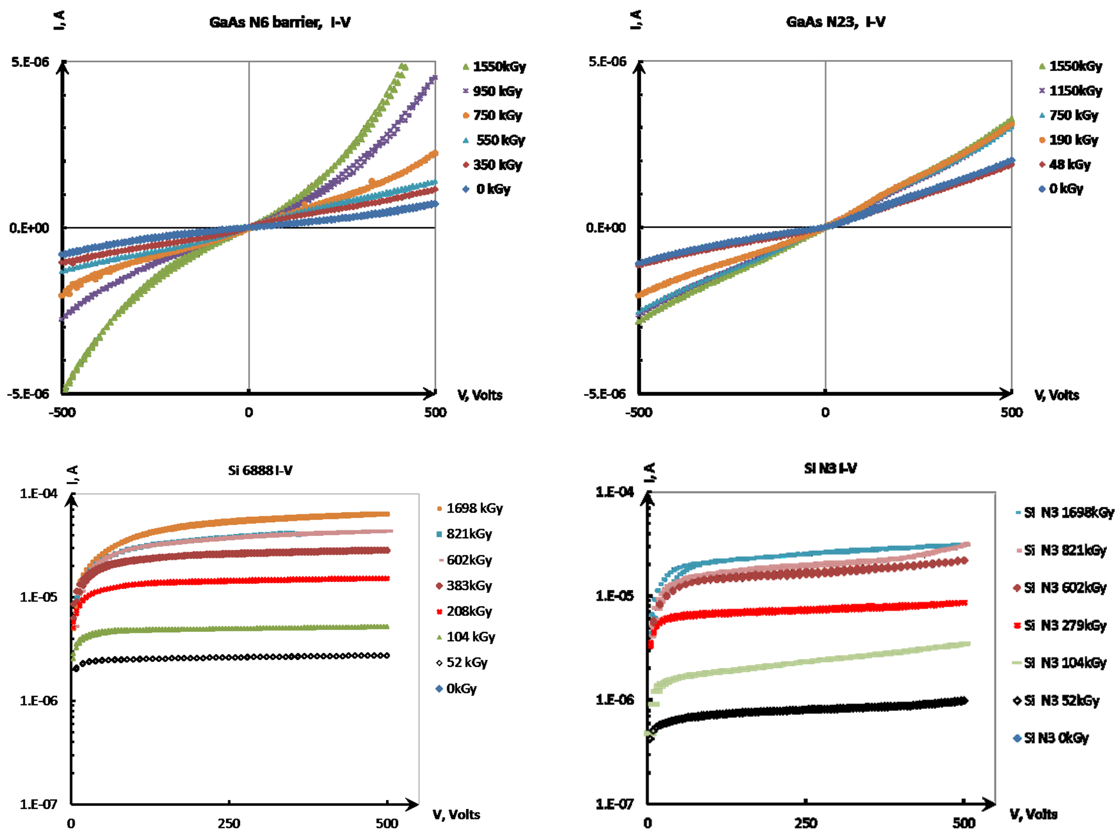


Figure 3: Current-voltage characteristics of detectors after irradiation. The upper row are gallium arsenide detectors (resistive structures on the left, barrier structures on the right), the lower row are silicon detectors (n-type silicon detectors from USCS (USA) on the left, the detectors provided by N. I. Zamyatin's group on the right).

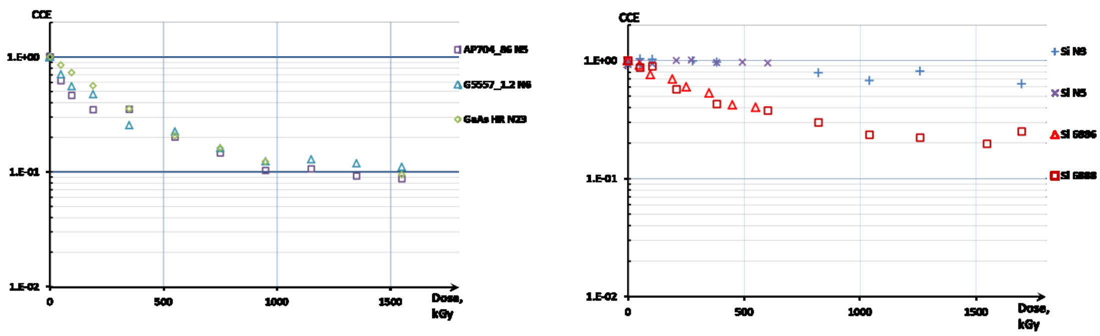


Figure 4: Dependence of the charge collection efficiency on the absorbed dose. Left - gallium arsenide detectors, right - silicon detectors.

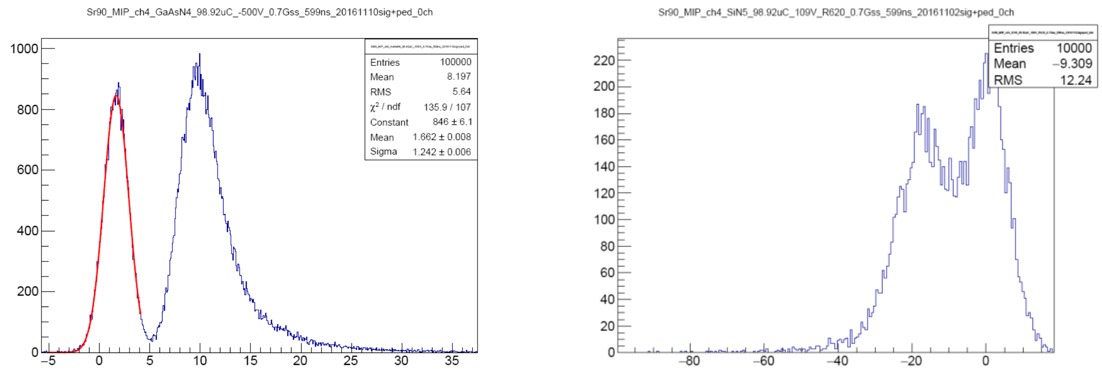


Figure 5: The spectra obtained on gallium arsenide (left) and silicon (right) detectors after irradiation with a dose of 0.5 MGy, at room temperature.

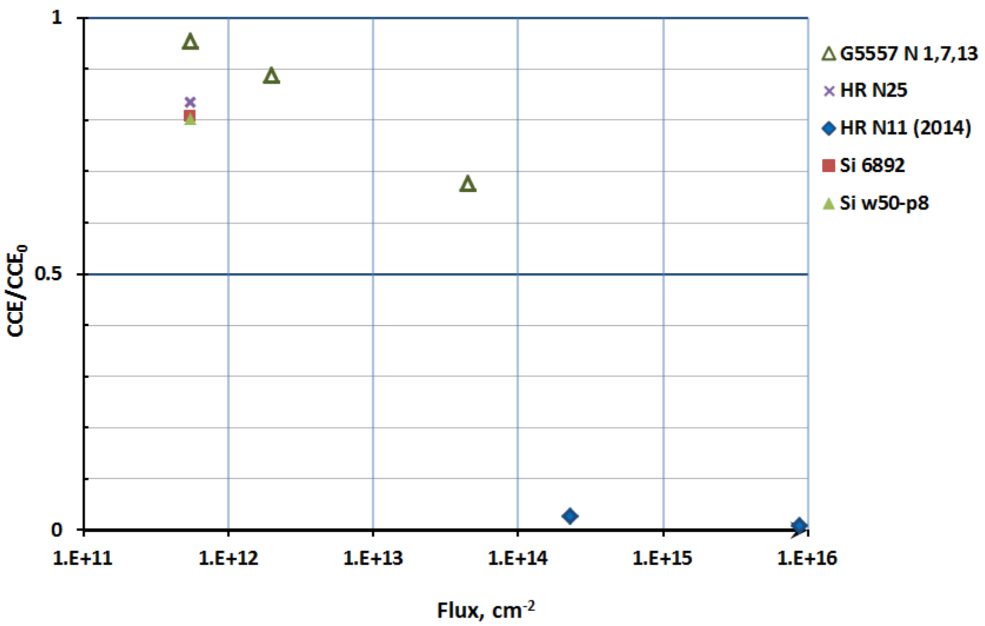


Figure 6: Dependence of the relative efficiency of charge collection on neutron fluence for silicon and gallium arsenide detectors.

2.1.2 Development of FCAL calorimeter for future electron-positron colliders

Preparing for future experiments at high luminosity electron-positron colliders (ILC, CLIC, FCC, CEPC) required additional research in order to develop special calorimeters for the forward region. These calorimeters should be compact, have a high spatial resolution for the separation of showers, high positioning precision and high speed. Since detectors in the forward region are subject to very high radiation load, they must have an unprecedented radiation hardness. Depending on the angular aperture and the performed task, several calorimeters are distinguished: Pair Monitor, BeamCal, LumiCal [17, 18]. The BeamCal calorimeter is the closest to the beam pipe, and accordingly, is subject to the greatest radiation load. It is designed to measure large amount of soft electron-positron pairs produced by the conversion of bremsstrahlung, and high-energy beam electrons to facilitate adjustment of the beam parameters. Development of these detectors is conducted by the FCAL international collaboration. To achieve the required characteristics, a compact sandwich calorimeter with a high degree of segmentation consisting of tungsten absorber and recording planes made of semiconductor detectors has been proposed.

In addition to studies of the radiation hardness of detectors based on gallium arsenide that are necessary for selection of the optimal material for the sensitive element of the compact sandwich calorimeter FCAL, some work on the production of tungsten absorber plates for a full-scale prototype of the calorimeter module was carried out at JINR. The main difficulty lies in the extremely high requirements for the flatness of the plates – less than 20 microns for the final version of the calorimeter. In 2015-2016, orders were placed for the production of trial batches of tungsten plates from two Russian suppliers and geometric parameters of the manufactured plates were measured using a three-axis coordinate measuring machine Zeiss Eclipse installed in a clean room at the NEOVP DLNP JINR (Figure 7).

In total, 5 tungsten plates were produced by one supplier and 2 plates by another supplier. For quality control, a measurement technique has been developed that makes it possible to achieve repeatability of the results within the range of 1.5-2 μm. As a result of the measurements, one vendor was selected who managed to ensure flatness within 35 μm (Figure 8), which is quite enough to produce a prototype of the forward calorimeter module. During 2017-2019, production and delivery for the FCAL collaboration of about 30 tungsten absorber plates are planned.

Figure 7: Measurement of the geometric parameters of the FCAL tungsten absorber plates using Zeiss Eclipse three-axis coordinate measuring machine.

2.1.3 X-ray imaging detectors of large area

The use of hybrid pixel detectors makes a revolution in the field of detecting photons from synchrotron radiation sources and from sources on X-ray free electron lasers. By all accounts, they are detectors of the future, as they give a significant improvement in image quality compared to current detectors based on CCD cameras. Examples are the large area detectors based on the readout chips Pilatus, Medipix and XPad, developed by various institutes in Europe. Due to commissioning of new sources of high-energy X-ray radiation, the demand for efficient material for sensors has grown rapidly over the last five years. The most promising materials for this region of X-ray energies are GaAs and Cd(Zn)Te. The medical imaging industry invests mainly in Cd(Zn)Te, since their main applications (human scanning) require high photon energies above 100 keV, which in turn requires sensors from high Z material. Synchrotron radiation sources have a large and growing emphasis on energy in the range up to 80 keV, for which GaAs is best suited.

As a continuation of the successful project GALAPAD (2011-2013) to develop a technology for the production of GaAs hybrid pixel detectors of the "Hexa" type (assembling 3×2 Medipix chips on a common sensor), in 2014 the joint Russian-German project GALAPAD-2 was started. The project aims to develop large area pixel detectors of the "Double-Hexa" type (assembly of 6×2 chips) with the area of the active region of 82×28 mm^2. This project involves JINR (with TSU as a co-executor) from the Russain side and DESY, the Karlsruhe Institute of Technology and the Freiburg Materials Research Center

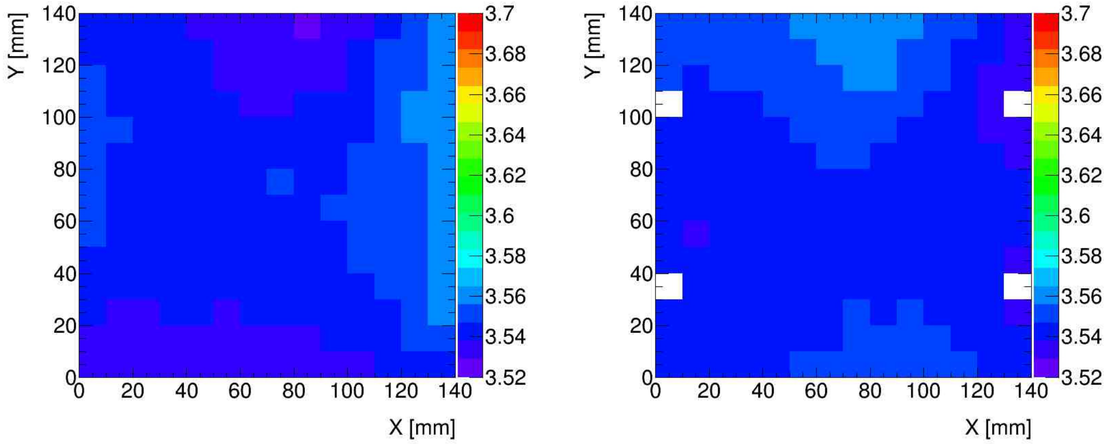


Figure 8: Results of measuring of the surface shape of the tungsten absorber plates for FCAL. The distance to the surface of the plate in mm is shown relative to the base plane for the two sides of the absorber plate.

from the German side. The project was supported by the Russian Ministry of Education and Science within the framework of the Federal Program "Research and development in priority areas for the development of Russia's scientific and technological complex for 2014-2020", with a funding volume of 47 million rubles in 2014-2017[1].

To fulfill this project, it is required to develop a technology for production of gallium arsenide sensor wafers of 4″ size, to develop methods for controlling the sensors quality, to improve the technology of mounting readout chips on a common sensor and to develop high-rate electronics for data acquisition. The detectors will have much reduced insensitive area at the edges of the sensor, which will allow to tile such detectors on four sides and use them as elements of detecting systems of arbitrarily large area. The detector modules will be tested on the synchrotron sources ANKA in KIT and PETRA-III in DESY. Additional experiments will be carried out to evaluate GaAs as a material for detectors for X-ray free electron lasers – in particular, the ability of GaAs detectors to withstand a high instantaneous flux appearing at high intensity radiation sources.

In the course of carrying out the GALAPAD-2 project, the following main results were obtained at JINR in cooperation with TSU:

- in JINR a modern test bench based on the Cascade Microtech EPS150TESLA probe station for studying properties of semiconductor materials has been created and put into operation;

[1]Agreement on granting subsidies from the Russian Ministry of Education and Science of September 17, 2014, No. 14.618.21.0001.

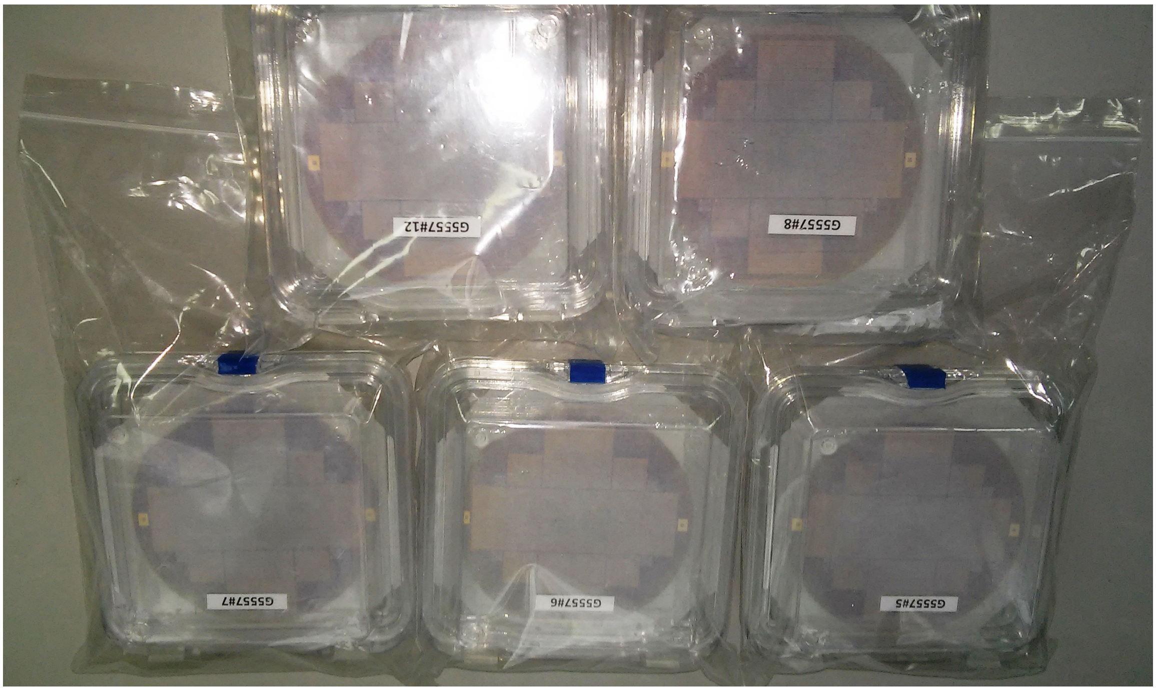


Figure 9: The first batch of GaAs:Cr sensor wafers with a diameter of 102 mm, produced within the GALAPAD-2 project.

- in TSU 40 sensor wafers with a diameter of 76 mm (one sensor of Hexa size on each wafer) made of modified gallium arsenide GaAs:Cr were manufactured for testing the dicing technology for a reduced size of the insensitive region at the sensor edges (slim-edge technology). At JINR, a visual inspection of the obtained sensor wafers was carried out under the microscope: eleven out of the forty wafers had either defects in metallization or mechanical damage. The characteristics of all the sensor wafers were measured on the probe station in order to discard wafers that were not suitable for subsequent use as sensors in hybrid pixel detectors;
- in TSU the technology of production of sensor wafers with a diameter of 102 mm from compensated gallium arsenide has been mastered, 17 sensor wafers of the Double-Hexa size have been manufactured to this day (Figure 9);
- JINR has become a full member of the Medipix-4 international collaboration;
- JINR filed patent Application No. 2016150633 dated December 22, 2016 for the invention "Semiconductor Matrix Detector for Charged Strongly Ionizing Particles (Multiply Charged Ions) " and patent studies were carried out.

In Germany, the technology of simultaneous bonding of 12 readout chips with a common sensor and the technology of dicing slim-edge sensors are being worked on, as well as the development of a high-speed Lambda data acquision module with a rate of 1000 frames per second. After completion of the work, one of the Lambda detector modules with a Double-Hexa sensor will be delivered to JINR.

The GALAPAD-2 project should be completed by the end of 2017.

During the year 2015, in addition to cooperation within the GALAPAD-2 project, 50 pixel sensors each with an area of 28×42 mm^2 (with the total area of about 600 cm^2), required to create a large area pixel detector to be used on the XFEL beamlines, were fabricated and tested within the framework of a separate collaboration between JINR-DESY-TSU.

2.1.4 Hybrid pixel detectors based on the Timepix readout chip

Development of the procedure for per-pixel energy calibration of Timepix detectors

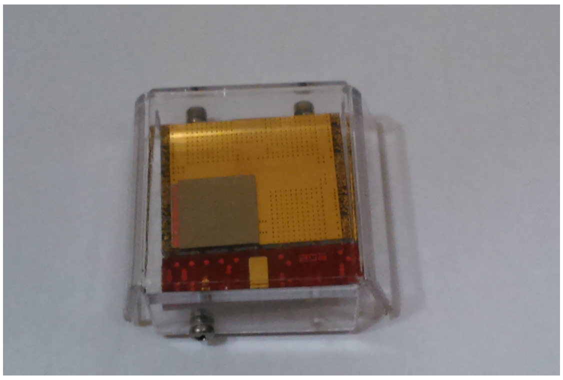
For energy calibration of Timepix detectors with GaAs:Cr sensors, a per-pixel calibration procedure was developed that uses characteristic lines in the X-ray spectra of various metals, which were accurately measured beforehand by a spectrometer based on germanium detector (LEGe Canberra GL0515R). The main advantage of using X-ray characteristic radiation is the high speed of acquiring the necessary set of data (the procedure can be repeated using a set of reference radioactive γ-sources, but the data collection time is increased by an order of magnitude).

Thanks to the use of per-pixel calibration, it was possible to achieve a good energy resolution of Timepix detectors with GaAs:Cr sensors: 8.5% at 59 keV. It was shown that further improvement in the calibration quality in the low-energy part of the spectrum (5-15 keV) can be achieved by increasing the number of reference points which are used in the fitting of the calibration curve in this region. Providing that the spread of parameters of detectors based on the Timepix chip is small, i.e. detectors give similar ToT[2] spectra with the same settings of the DAC and at a stabilized temperature of the sensor, the per-pixel calibration of the detectors can be carried out in the almost automated mode. To accomplish this task, special software has been developed. This feature is especially relevant for installations with a large number of Timepix detectors.

Investigation of Timepix pixel detector with 1 mm thick gallium arsenide sensor

In 2015, the first Timepix detector with a 1 mm thick gallium arsenide sensor was manufactured at JINR in cooperation with TSU and CTU (Prague). The assembly quality

[2]Time-over-Threshold – the duration of the signal above the threshold, proportional to the energy deposited in the sensor.



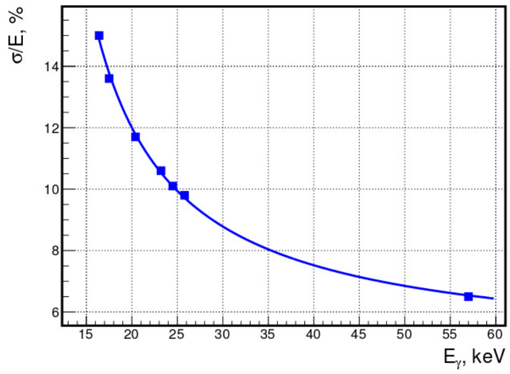


Figure 10: General view and energy resolution of the Timepix detector with 1 mm thick gallium arsenide sensor.

was very high (99.9% of usable pixels). As a data acquisition system we used the RelaxD[3] chip-board. The per-pixel energy calibration was performed according to the method developed at JINR. The energy resolution of the detector is 12% at 20 keV and 7% at 60 keV (Figure10). The accuracy of the energy scale is better than 1% for gamma quanta with energies below 100 keV. Figure 11 shows the emission spectrum of the ^{137}Cs source measured by this detector. One can see that the energy resolution is 4.8% at 660 keV.

Investigation of long-term stability

In mid-2015, the program to measure the long-term stability of Timepix detectors with gallium arsenide sensors was started. The measurements were made as follows. A standard radioactive source of ^{241}Am was placed at a distance of 1 cm from the surface of a Timepix detector. Measurements of the energy spectrum of the source continued throughout the year, while analyzing changes in the position of the photopeak at 59 keV, determined for both all the pixels as a whole and for several separate zones of the sensor. It was shown that the position of the photopeak moved during the year by less than 1 ppm (Figure 12). Simultaneous recording of the temperature allowed to conduct parallel measurements of the temperature dependence of the detector response (Figure 13). The obtained results lead to the conclusion that the spectrometric capabilities of the Timepix gallium arsenide detector are highly stable.

[3]Manufacturer - Amsterdam Scientific Instruments, The Netherlands.

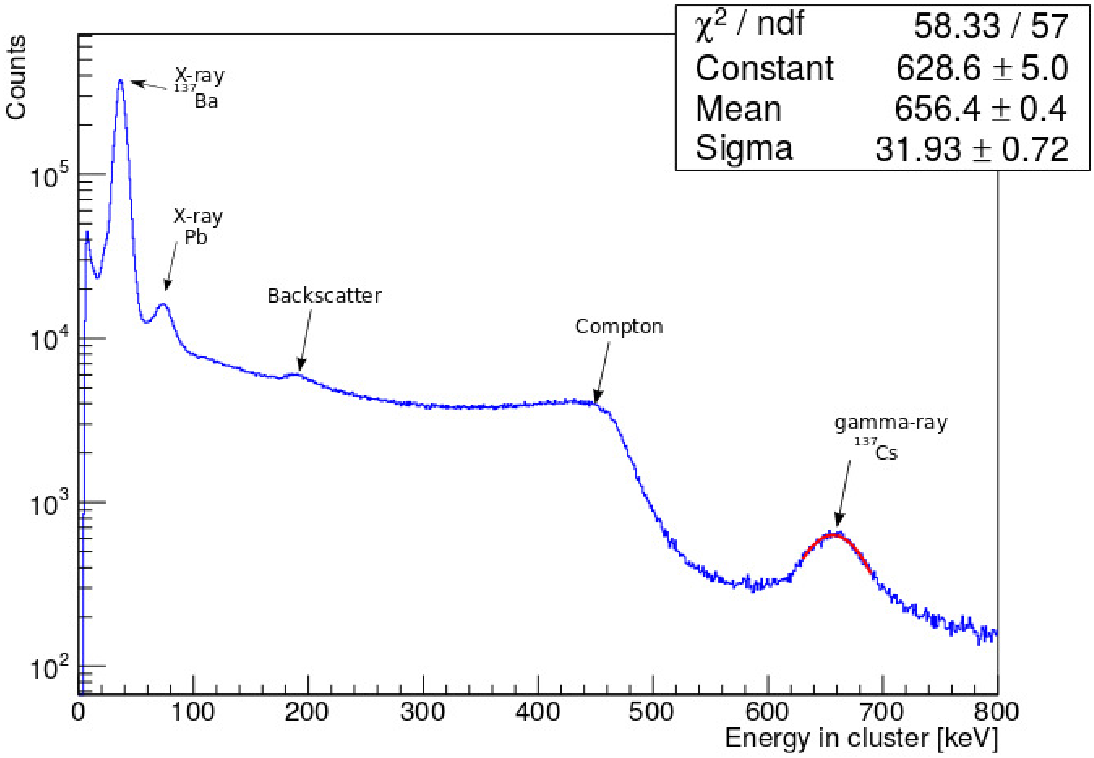


Figure 11: Spectrum of ^{137}Cs after the per-pixel energy calibration of the Timepix detector with 1 mm thick gallium arsenide sensor.

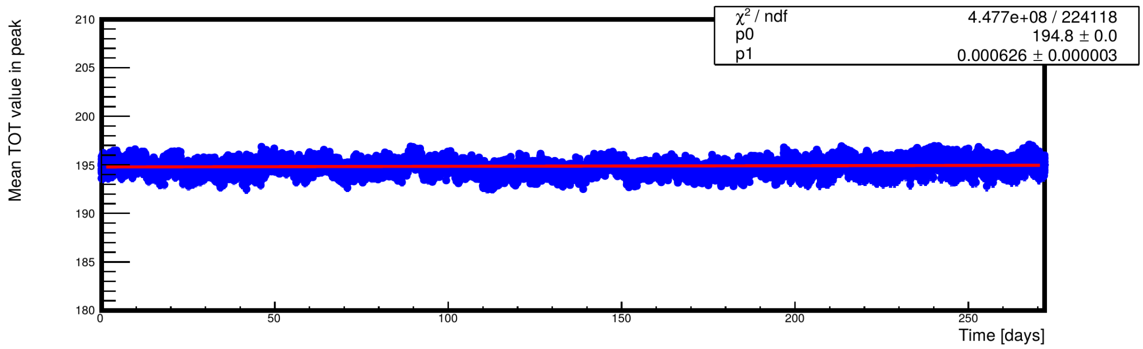


Figure 12: Change in the position of the 59 keV photopeak of an ^{241}Am source as a function of time.

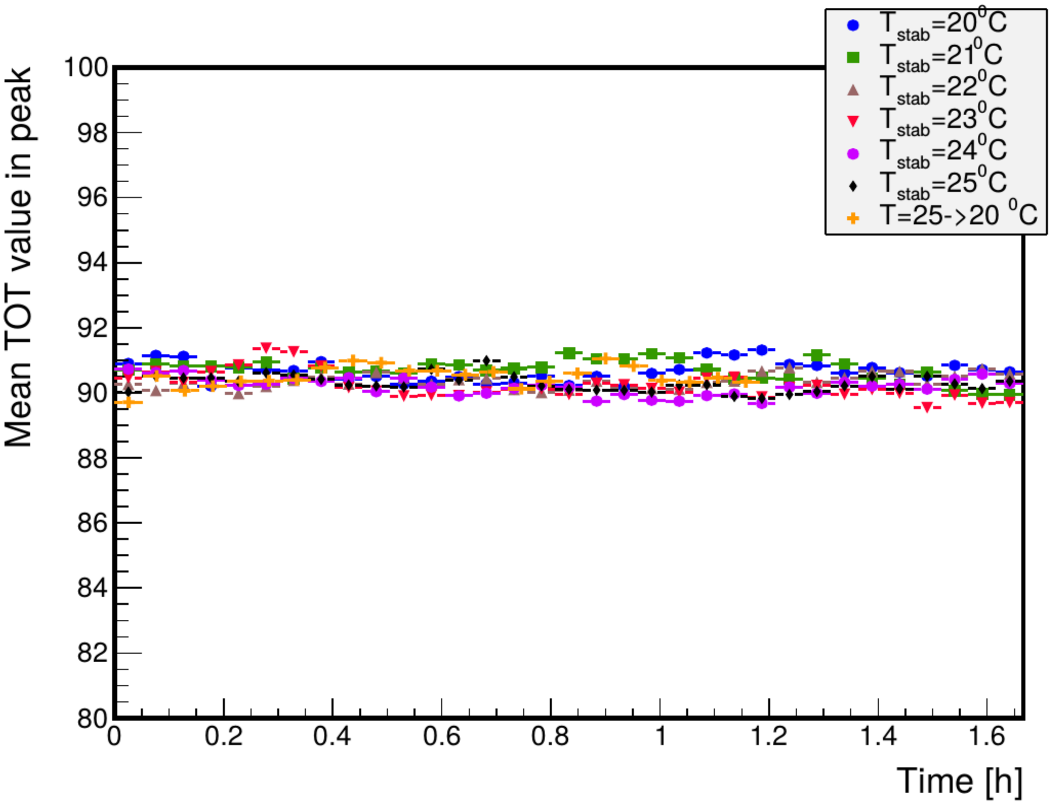


Figure 13: Stability of the position of the 59 keV photopeak of an ^{241}Am source at different temperatures.

Measurement of sensor transport characteristics in a pixel detector

An important characteristic that determines the collection of charges in a semiconductor detector is the product of the lifetime of nonequilibrium carriers τ by their mobility μ. In the course of the project, a method for determining $\mu\tau$ of electrons in gallium arsenide for pixel detectors was developed, based on the use of a beta separator (a source of monoenergetic electrons). The operation of the beta-separator is based on selection of a given energy from a wide spectrum of β-electrons formed in the radioactive decay of ^{90}Sr with the help of an electron collimator. The obtained dependences are shown in Table 2.1. It should be noted that the ability to reliably detect a signal from electrons with an energy of 100 keV shows that in gallium arsenide the thickness of the 'dead 'layer is not more than 24 μm - the mean free path of electrons of this energy.

E_e [keV]	Range [μm]	$\mu_e\tau_e$ [cm^2/V]
100	24	(1.2 ± 0.05)x10^{-4}
300	143	(1.4 ± 0.05)x10^{-4}
780	450	(1.9 ± 0.02)x10^{-4}
1700	881	(2.7 ± 0.06)x10^{-4}

Table 2.1: Changes of the $\mu\tau$ value with the varying thickness of the sensor. The electrons penetration depth is determined by their energy.

The use of X-ray fluorescence on zirconium foil makes it possible to measure $\mu\tau$ separately for each pixel. For 15.7 keV gamma-ray (the K_α line of zirconium) the attenuation length in gallium arsenide is less than 25 μm, which suggests that most of the interactions occur directly near the cathode. Measuring the dependence of the photopeak position on the bias voltage for each pixel and approximating it with the Hecht curve one can determine the value of $\mu\tau$ [23]. The results are shown in Figure 14. The average value of the product $\mu\tau$ for electrons in the gallium arsenide sensor is $1.1{\cdot}10^{-4}$ cm^2/V with the variance of $1.5{\cdot}10^{-5}$ cm^2/V.

Studies of pixel detector response with synchrotron radiation

In 2016 several measurements with hybrid pixel detectors were performed on the synchrotron radiation beamline of the VEPP-3M accelerator (Budker Institute of Nuclear Physics, Novosibirsk). This allowed us to experimentally investigate the behavior of gallium arsenide pixel detectors at high loads, as well as measure characteristics of the detector in the Medipix mode (counting individual photons) using a collimated monochromatic

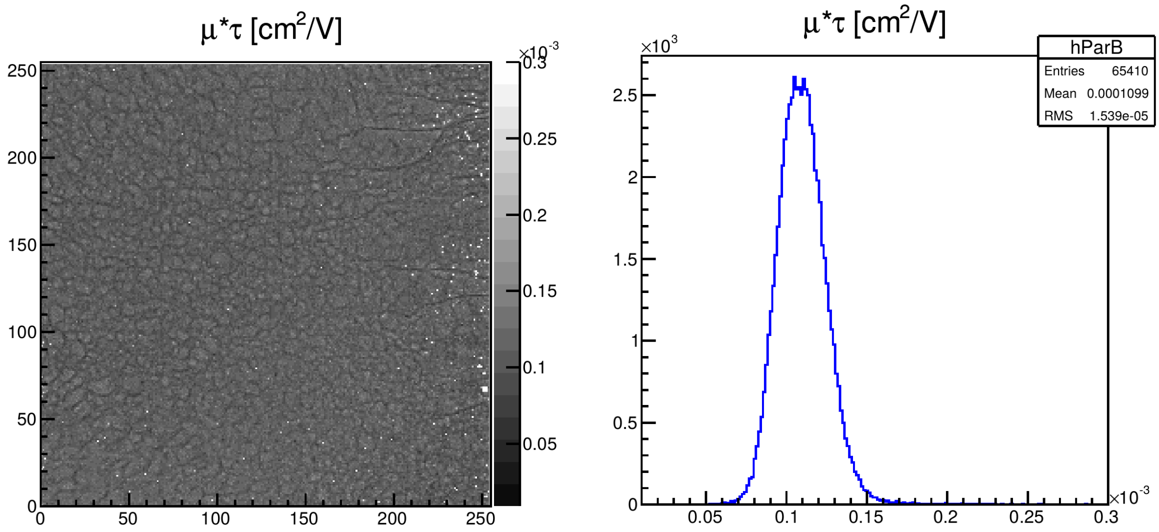


Figure 14: The value of $\mu\tau$ depending on the pixel position (left); distribution of the $\mu\tau$ values for all pixels in the detector.

X-ray beam. The experiment was carried out at the synchrotron station "Tomography and microscopy" with monochromatic photons, whose energy varied in the range of 6-40 keV with the spread of $dE/E = 0.072\%$. The use of the collimator made it possible to obtain a parallel beam with a transverse size of 10 μm $\times$ 10 μm. Precise positioning of the detector allowed to direct the beam to the desired part of the pixel.

The dependence of the energy resolution of the detector on the photon energy is shown in Figure 15 for three cases: for the photons hitting the geometric center of a pixel, averaged over all photons for the detectors with a sensor of 300 μm and 900 μm thickness. The best result of 4.5% at 18 keV is achieved for the photons hitting the center of the pixel.

2.1.5 Pixel detectors as elements of tracking systems

Pixel silicon detectors are a promising tool for creating tracking systems which are already actively used in high energy physics. One of possible applications is the investigation of the electromagnetic dissociation of the carbon isotope ^{9}C, namely, determination of the probability of its fragmentation into three ^{3}He. The VBLHEP has prepared a rig for the telescope made of 4 silicon detectors based on the Timepix chip. In this setup the first detector is rotated almost parallel to the beam, therefore it serves simultaneously as a tracking detector and a target. With such a rotation angle, incoming particles are visible and ^{9}C can be identified, the interaction point and outgoing tracks are visible too. In the VBLHEP experiments, the cross section of the interaction of carbon with silicon was

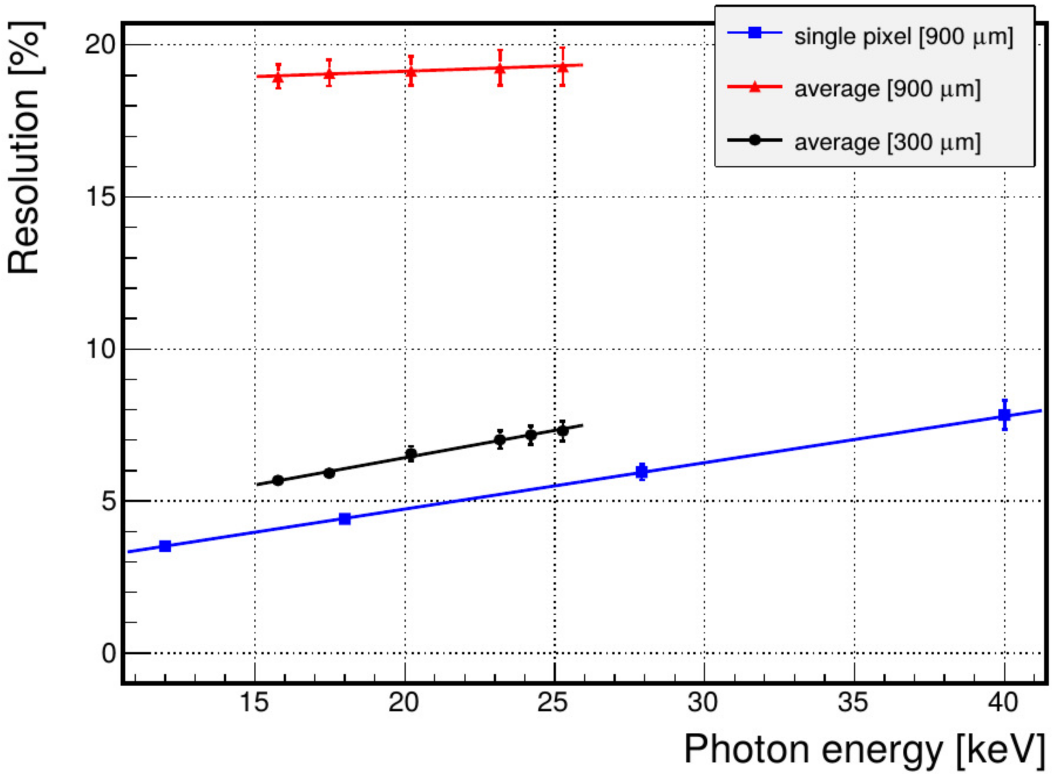


Figure 15: The dependence of the energy resolution of the detector (expressed as a percentage of the measured energy) on the photon energy.

measured, so one can expect one interaction in such a detector per 1000 incoming particles. The main tasks of this activity are mastering the technique of working with detectors, studying the Coulomb dissociation of radioactive nuclei and their fragmentation. The accuracy of track reconstruction in the telescope depends on the shape of the cluster and can reach 2-3 microns. It should be noted that with the help of this method it is possible to study a number of processes which earlier were possible to study only with the help of photoemulsions. The main limiting factor hindering the use of the telescope in this experiment is the low rate of the readout electronics, so it is highly desirable to replace the electronics with a faster one.

In the course of the Project, Timepix detectors were tested on a beam of ^{12}C carbon nuclei with an energy of 1.2 GeV/nucleon at the JINR Nuclotron. Distributions of cluster sizes and energy losses were obtained. A relative equalization of Timepix detectors in the telescope has been carried out. The measurement of the number of δ-electrons on the length of the Timepix detector showed that the methods used to determine the nuclear charge by the number of δ-electrons in photoemulsions can not be directly transferred to pixel detectors and need to be modified.

This work is carried out in cooperation with a group from the Czech Technical University (Prague).

2.2 Research program for 2018-2020

2.2.1 Searches for methods to increase the radiation hardness of gallium arsenide detectors

The obtained in 2016 measurement data on the radiation hardness of detectors will be used to develop a GaAs:Cr radiation damage model and, in the future, to find ways to increase their resistance to irradiation. The main reason for the deterioration of detector properties of gallium arsenide is the formation of defects in the crystal lattice, with different types of irradiation leading to different types of defects and different rate of their appearance. As measures to increase radiation hardness, the introduction of doping impurities that compensate for the effect of defects on charge collection is usually considered. Since this method (chromium compensation) is the basis for the production of high-resistive gallium arsenide, there is a certain hope of increasing the radiation hardness of this material by changing the chromium compensation technology or introducing additional impurities. However, this requires quantitative measurements of the rate of formation of various types of defects for different types of irradiation and dose rate. The existing measurement methods – current-voltage and capacitance-voltage characteristics, the charge collection efficiency – of course, give certain information, but do not allow us to distinguish the types of defects that are formed. To solve this problem, it is planned to establish at DLNP during 2018-2019 a station for carrying out measurements using the methods of deep level transient spectroscopy (DLTS).

When these studies are performed, additional irradiation sessions of samples are planned on the electron beam of the Linac-200 accelerator, the neutron beams of the IBR-2M reactor, and possibly other sources of radiation.

These works will be carried out in cooperation with TSU and the Institute for Space Research (Bucharest-Magurele, Romania).

2.2.2 Identification of particles in hybrid pixel detectors

Differences in the nature of interactions of charged particles of different types with matter (different path, scattering probability, amount of energy released) lead to a visible difference in the shape of the clusters and the magnitude of the signal on the pixel detectors (Figure 16). These differences can be used to identify particles by their response.

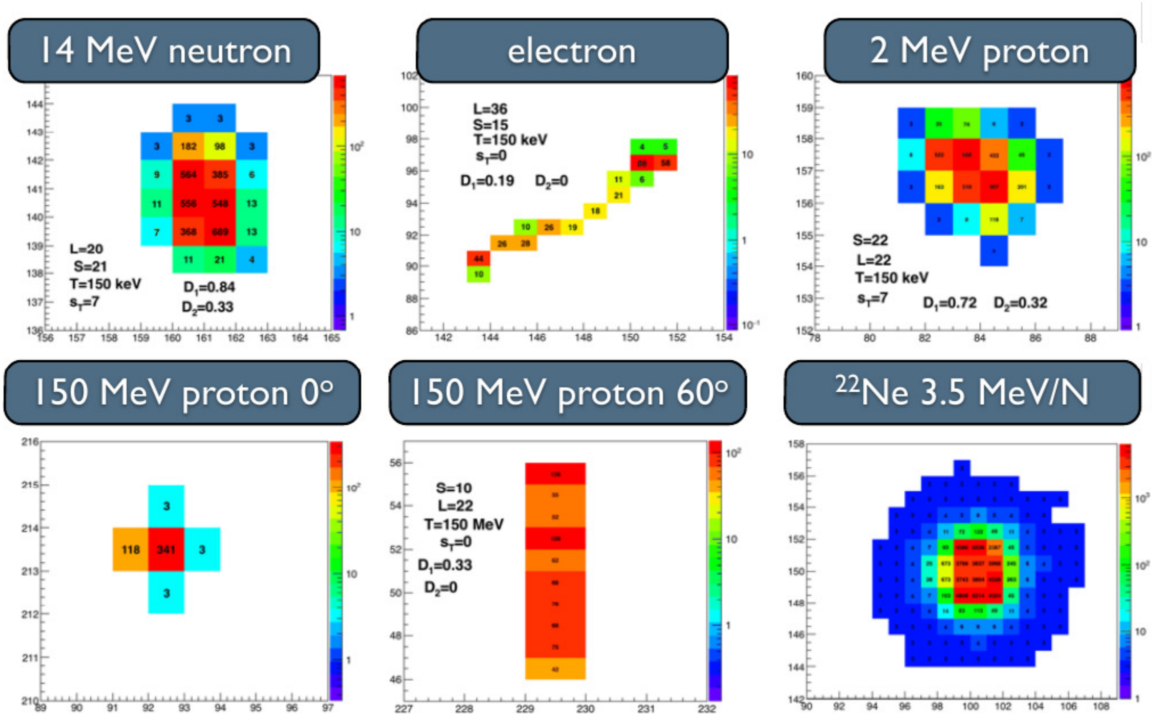


Figure 16: Typical clusters formed in Timepix detectors by different types of particles.

In the course of the Project, many data runs were conducted with the Timepix detector on the beams of different JINR and CERN facilities for different types of particles: X-ray and high-energy gamma quanta, electrons, protons, alpha particles, neutrons, deuterons and heavy ions of various energies. As a result, a new method of particle identification was developed to separate interactions having electromagnetic or nuclear nature. For separation, two parameters D1 and D2 are used. The parameter D1 is calculated as the ratio of the cluster area to its perimeter and characterizes the shape of the cluster. The parameter D2 is calculated as the number of pixels with energy release above a certain threshold to the total number of pixels in the cluster and characterizes the ionization losses of particles. An example of the separation is shown in Figure 17.

During the implementation of the Project in 2018-2020, it is planned to improve the procedure for particle identification and to obtain numerical estimates of the efficiency and purity of the obtained separation.

2.2.3 Neutron registration

Detection of neutrons and determination of their spectrum with the help of Timepix detectors have great practical importance. Although in the case of thermal neutrons the possibility of recording them using various converters has been successfully demon-

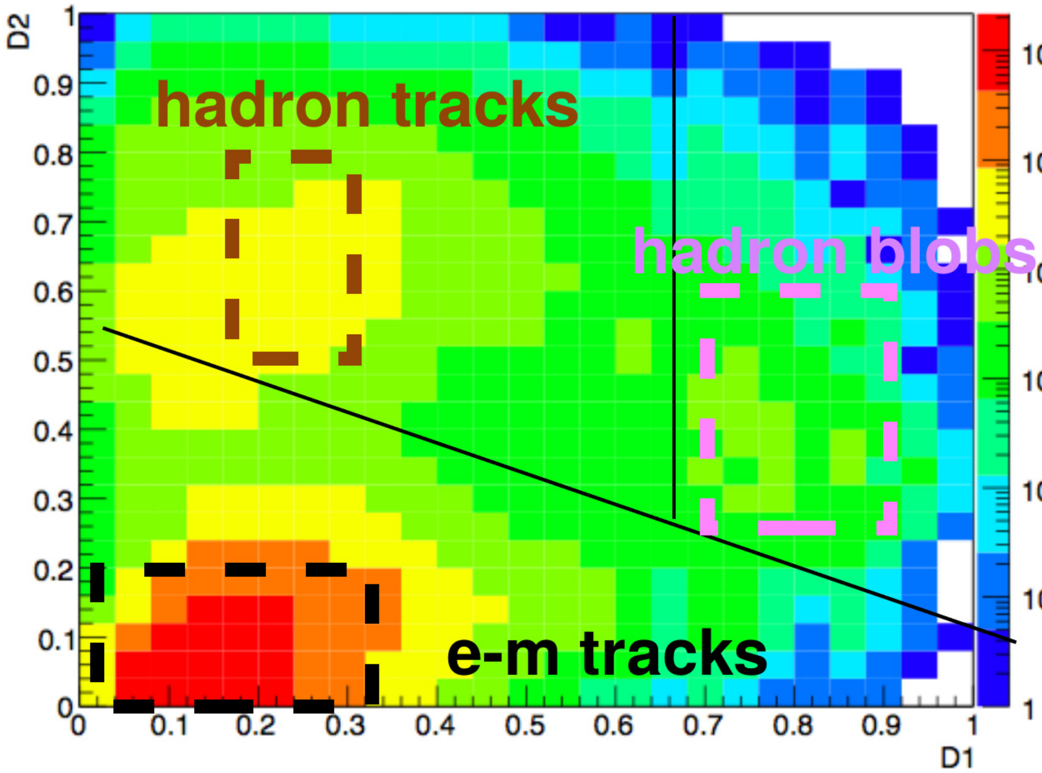


Figure 17: Separation of cluster types in the Timepix detector based on parameters D1 and D2.

strated [20, 24, 25], registration and determination of the fast neutron spectrum is a more difficult task.

In the fall of 2015, during the course of the Project, the response of a Timepix detector to neutrons was investigated on a neutron beam of the n_TOF facility in CERN. Detectors with a sensor made of silicon and gallium arsenide were irradiated with neutrons with energies from 1 eV to 1 MeV. Using the time-of-flight information, the neutron spectrum recorded by these detectors was reconstructed (Figure 18). To do this, Timepix detectors were set to work in mixed mode (every 9th pixel measured not the amplitude of the signal, but the time from the beginning of the signal to the end of the frame).

During 2018-2020, it is planned to carry out additional measurements and experimentally determine the dependence of neutron detection efficiency of gallium arsenide detectors on neutron energy, and also to study the use of several converters with different neutron-induced thresholds for determination of the fast neutron spectrum.

The results of this work will be especially useful when analyzing and interpreting data coming from the GaAsPix [26] radiation background monitoring system installed in the

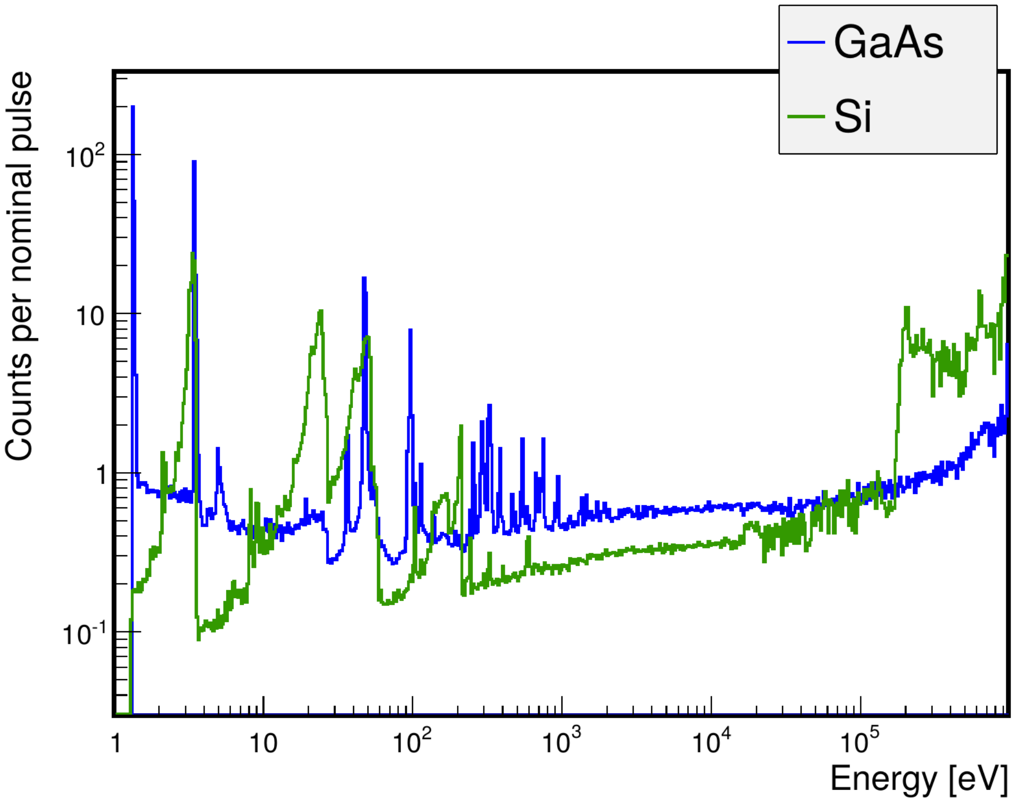


Figure 18: Spectrum of neutrons in Timepix detectors with sensors from silicon and gallium arsenide.

ATLAS cavern at the LHC.

2.2.4 Studies of hybrid pixel detectors response to the passage of heavy charged particles

Although the response of Timepix silicon detectors to the passage of heavy ions was studied by several groups [27, 28], up to now there was no information on the response to heavy ions of similar detectors with a gallium arsenide sensor. In particular, the use of Timepix silicon detectors for detecting heavy ions has shown the presence of the so-called "volcano effect" - deformation of the cluster profile in the region of maximum energy release (Figure 19).

During the implementation of the Project, a series of measurements was carried out on the beams of the U-400M FLNR accelerator, in which Timepix detectors with silicon and gallium arsenide sensors were irradiated with various heavy ions at different beam energies. As a result of these measurements, it was shown that there is no "volcano

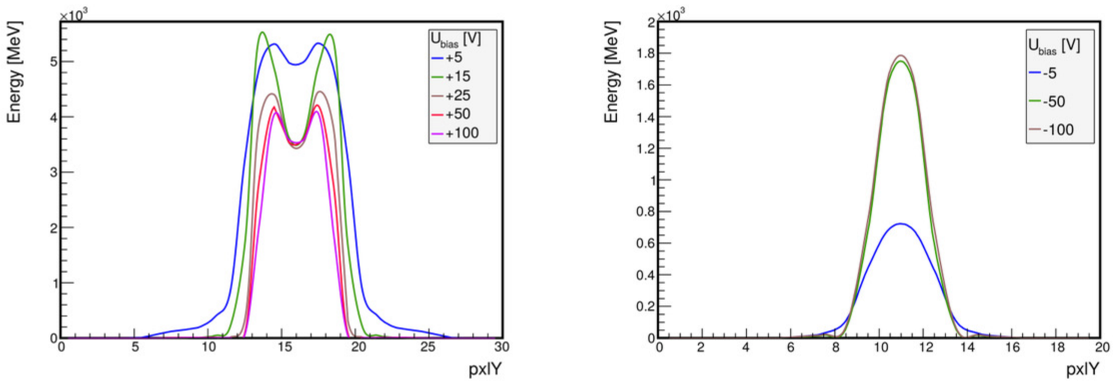


Figure 19: "Volcano effect" in the silicon (left) and gallium arsenide (right) Timepix detectors when irradiated with Ne ions with an energy of 158 MeV.

effect" in gallium arsenide detectors (Figure 19), but there is a large non-linearity in the measurement of energy, related both to the saturation of the readout preamplifier and to physical processes in the sensor itself. This makes difficult calibration of the detectors and complicates accurate measurements of the ion energy.

During 2018-2020, it is planned to study in detail the mechanism of the formation of the Medipix detector response to the passage of heavy charged particles releasing high energy and to develop reliable methods for measuring the energy and coordinates of particle interaction. It should be noted that the large cluster size (several dozen simultaneously triggered pixels) allows to significantly increase the spatial resolution of the detector by finding the center of gravity of the pixels in the cluster.

Development and verification of the methods for determining characteristics (intensity, profile, particle composition) of heavy ion beams using the Medipix detector in the energy range from 5 keV to 10 MeV per nucleon will be useful for the creation of heavy ion beam diagnostic equipment, in particular, for measuring the energy of the incident beam and for the creation of positionally sensitive detectors for monitoring and visualization of the profile of a heavy ion beam.

2.2.5 Application of pixel detectors in experiments with hypernuclei and relativistic ions on the Nuclotron

For experiments on the Nuclotron, a new polarimeter for the source of polarized deuterons is needed. The polarization of the beam should be measured both directly behind the linear accelerator LU-20 and in the Nuclotron ring. The polarization is measured by determining the "left-right" asymmetry in the scattering of ions at a given angle. It is proposed to use the Timepix detector as a sensitive element of the new polarimeter. The intensity of scattered particles is of the order of 100 Hz, which is quite acceptable for such a detector. Compared to the existing electronics, which can only work at a flow rate of no more than 10 Hz, the new system will allow to reduce the measurement time by an order of magnitude and simultaneously improve the accuracy due to the higher spatial resolution of the Timepix matrix. A new polarimeter based on the Timepix detector is planned to be manufactured and installed during 2017-2019.

Chapter 3

Research infrastructure in the DLNP of JINR

3.1 Main results in 2015-2017

3.1.1 “Kalan” measuring station

The “Kalan” measuring station is designed for detector calibration and for studies of the response of detectors using X-rays and, in the future, closed radioactive sources. The station consists of an X-ray protected locker equipped with an automatic switch-off system when the doors are opened, in which the radiation source and the detector under investigation are connected to a data acquisition system and a high voltage supply (Figure 20). Microfocus X-ray tubes RAP-150MN or SourceRay SB-120 with operating voltage up to 150 and 120 kV, respectively, controlled by a PC are used as a source of radiation, alongside with radioactive sources.

3.1.2 Testing bench based on a probe station

In 2015, a testing bench based on the Cascade Microtech EPS150TESLA probe station was developed and put into operation for studying properties of semiconductor materials. Preliminary renovation work was done in the clean room where the test station was installed: the floor was reinforced, the ventilation system was updated, compressed air and vacuum systems were cleaned, and the grounding loop was improved. These measures are needed to ensure stability of the necessary environmental conditions in the clean room for the normal operation of the probe station. In the clean room a metal frame on two concrete supports was installed, covered with a 5 mm steel sheet, as a base for the probe station mounting. All components of the testing bench (the probe station itself, the module for high voltage supply, the Keithley 2400 picoamperemeter, the Keysight (Agilent) E4981 capacitance meter, the temperature regulator) were installed during the

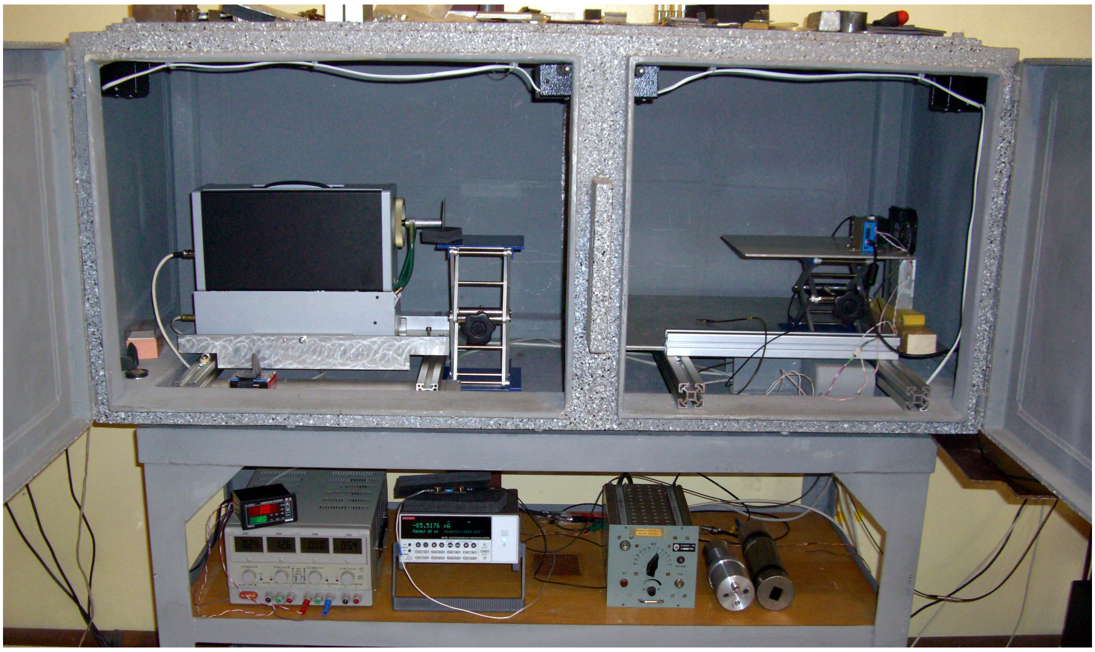


Figure 20: “Kalan” measuring station.

year 2015. Figure 21 shows the general view of the created test bench.

The testing bench allows to measure the current-voltage and capacitance-voltage characteristics of the samples under study in patches up to 5 μm $\times$ 5 μm in size. The range of the measured currents is from 0.1 nA to 100 mA at a bias voltage up to 1 kV with the measurement accuracy being better than 5

3.1.3 Station for measuring charge collection efficiency

To measure the efficiency of charge collection, a special station was designed and created. The operation of the station is based on the passage of a collimated electron beam from a radioactive β-source ^{90}Sr with subsequent acquisition and analysis of the signal in the detector under investigation using the DRS4 module. Trigger signal is formed on the basis of the response of two scintillation counters, that allow to measure the efficiency of charge collection up to extremely low values (less than 1%) due to suppression of background random triggers. At the same station, it is possible to measure the current-voltage characteristics of the detector. Measurements are quite fast: the measurement time of charge collection efficiencies is usually about 15 minutes, the time for determining current-voltage characteristics is about 10 minutes. On the station it is possible to perform characterisation of detectors that are not firmly fixed to a printed circuit board.

The scheme of the device and the photograph of the station are shown in Figure 22.

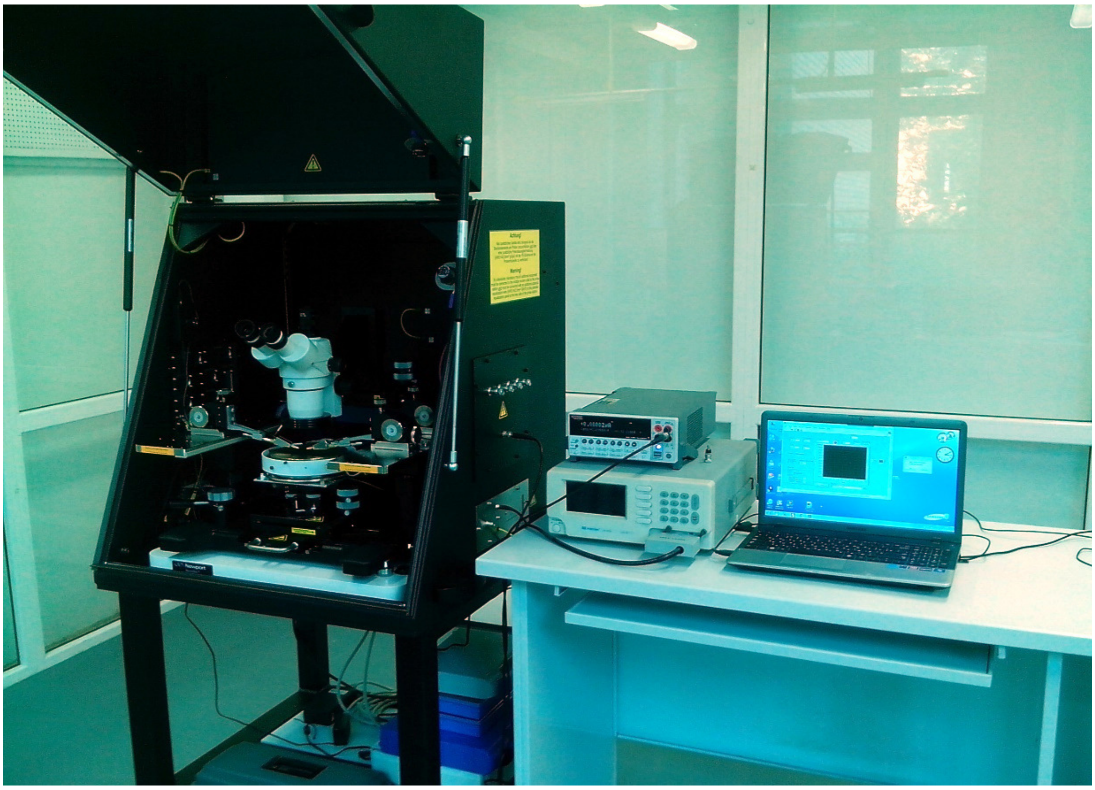


Figure 21: Testing bench based on the Cascade Microtech EPS150TESLA probe station for studying properties of semiconductor materials.

3.1.4 Installation for ultrasonic microwelding

A detector of the Medipix family consists essentially of a readout chip and a semiconductor sensor bonded by the "flip-chip" method. Such an assembly is mounted on a printed board connected to data acquisition electronics. The formation of electrical connections between pads of a printed board and leads of a Medipix chip are carried out using wire jumpers. In the same way, pad detectors are mounted.

For installation of detectors on printed circuit boards and for small repairs, the semi-automatic TPT HB-16 ultrasonic welding machine was purchased and put into operation in 2015 (Figure 23). For each material (Ni, Al, Cu) of the substrate, a particulat mode of thermosound micro-welding is selected using aluminum wires with a diameter of 20-25 μm (Figure 24). This installation is universal and can be used for assembling other detectors (for example, microstrip and pad ones), for other JINR laboratories and participating countries. To ensure the quality of the assembly of detectors, the TPT HB-16 is placed in a clean production room of class 10,000 according to the 209D standard. The room was used earlier for the production of drift chambers for the muon spectrometer of the ATLAS

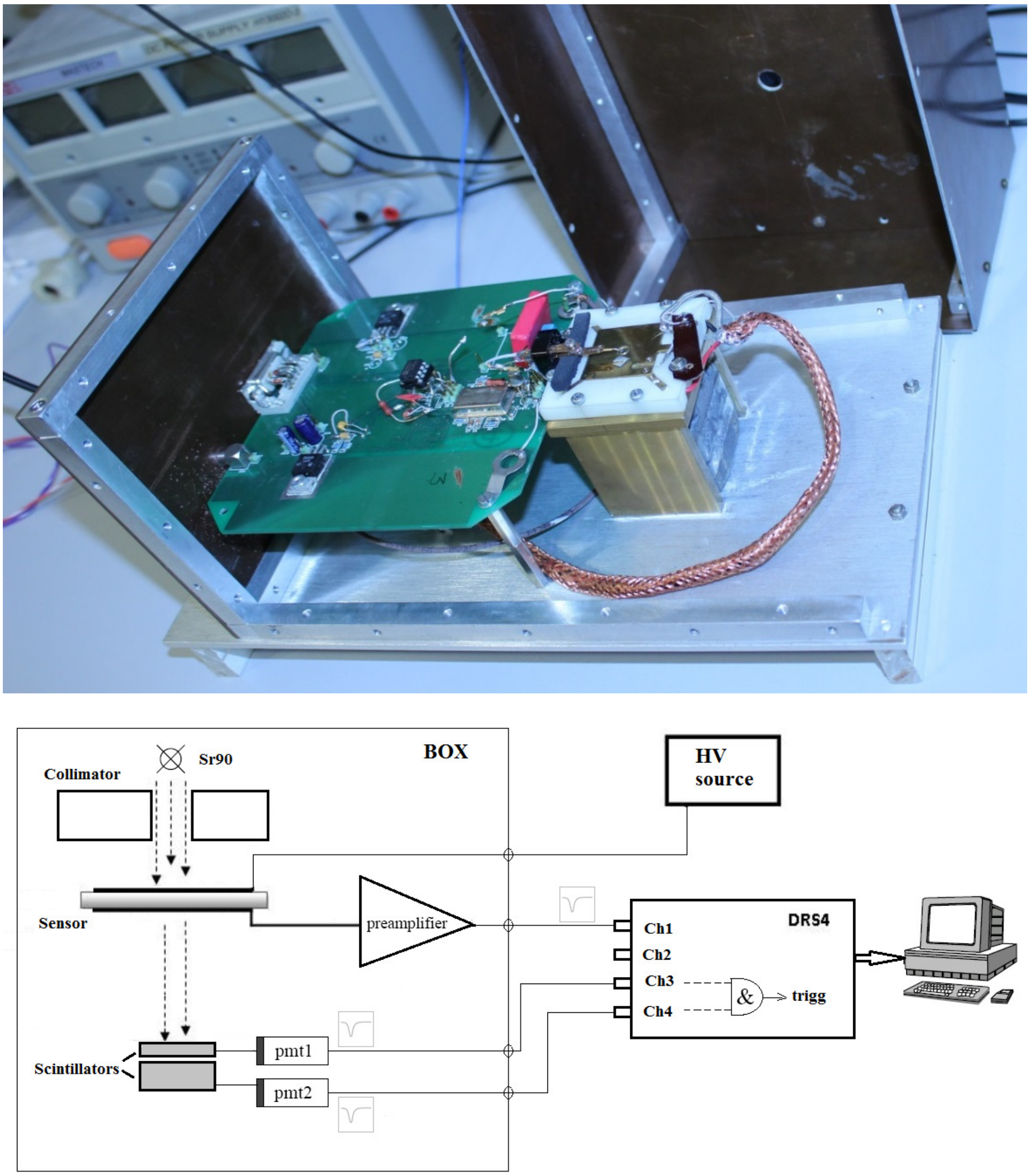


Figure 22: Station for measuring charge collection efficiency.

Figure 23: Installation for ultrasonic microwelding.

detector in 2000-2003. In the course of this project, the clean room has been modernized: the floor covering has been replaced, the ventilation and air purification components have been replaced, the automatic temperature control system has been replaced, and a climate monitoring system has been installed inside the clean room.

3.1.5 Feasibility studies of the site for assembling of hybrid pixel detectors

In accordance with the initial goals of the Project, which included the creation in the DLNP of a specialized laboratory for the assembly of detector prototypes, in 2015 a proposal for the assembly site was developed that would allow small-scale production of hybrid pixel detectors in JINR. In the case of cooperation with TSU and IHEP, the proposal would allow to implement the complete technological chain for the production of such detectors on the territory of the Russian Federation.

In the full version, the laboratory for the assembly of hybrid pixel detectors includes:

- chemical treatment and photolithography site (wafer cleaning, wafer exposure, etching),
- magnetron installation for deposition of a metallization sublayer,

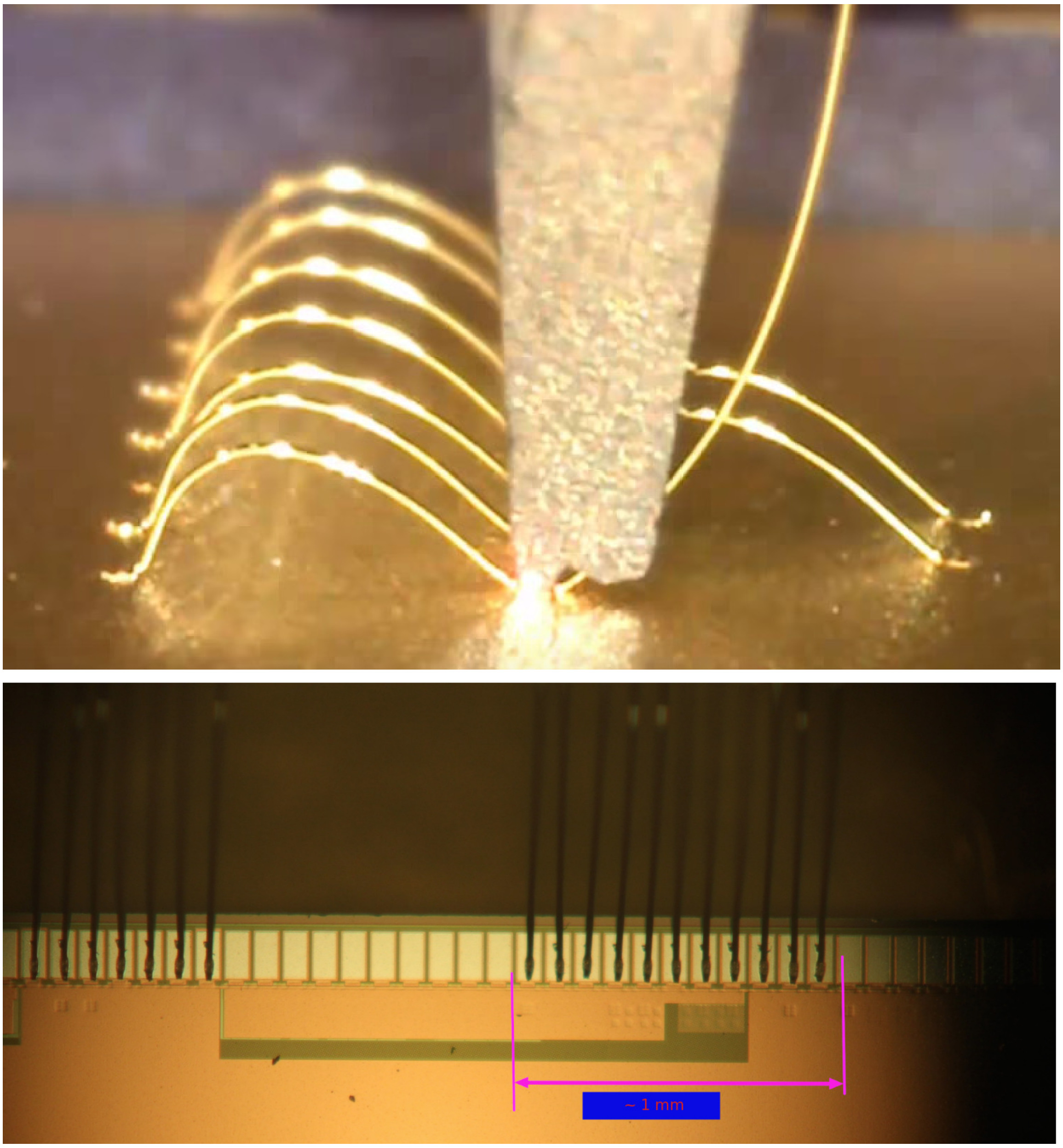


Figure 24: An example of creation of micro-wire connections by the “wedge-wedge” method (above) and an example of the connections of the Medipix chip to a chipboard (below).

- installation for the formation of microcontacts (bumps),
- wafer cutting machine,
- installation for high-precision alignment and assembly of detectors.

For the installation of the equipment it was planned to allocate a working area of 30 m^2 in the existing clean room with a class of cleanliness 100. Chemical treatment should be carried out in a separate room. Quality control can be assured using the existing test stations.

As a result of the work, relevant equipment was selected, a feasibility study and a site deployment plan were prepared. The total cost of creating such a site was estimated to be 1.98 MUSD (in prices of 2015).

Due to the relatively high cost, the decision to create the site was postponed until the need for a small-scale production of pixel detectors at JINR is clear. Within the framework of this Project, it is planned to improve mainly the measuring stations and the installations for minor repairs of existing detectors (the installation for ultrasonic micro-welding and a future installation for BGA-mounting). The production of the detectors themselves will continue to be carried out by outside organizations, using the existing international cooperation.

3.2 Scanner for microtomography

During the implementation of the Project, a work to improve the MARS X-ray micro-tomograph was carried out with the greatest efforts being put into development of its software.

The software for the MARS CT scanner was significantly improved that drastically increased the reliability and flexibility of the existing equipment.

To improve the quality of tomographic images, special software was developed to preprocess the received projections, including:

1. stitching of large projections from individual frames;
2. open field normalization;
3. filtering of noisy and inadequately working pixels over open and dark fields;
4. calculation of pairwise difference projections for consecutive energy thresholds;
5. the transformation of data from projections to synograms;
6. filtering of ring artifacts from synograms.

Along with the use of the commercial software Octopus[1], a proprietary implementation of the approximate FDK (Feldkamp, Davis, and Kress, 1984) reconstruction algorithm for the cone-ray tomography was developed at JINR to process received projections and reconstruct cross sections of samples. The simplicity of the algorithm makes it widely applicable in CT, but in view of the computational complexity, the recovery of image slices takes considerable time. The priority task is to reduce the projections processing time and reconstruct images of the sample without losing the quality of the reconstruction. In this regard, parallel implementations of FDK were developed for performing calculations on heterogeneous computing systems using OpenMP technology. An architecture with task management (the OpenMP tasks mechanism) was used to organize the optimal allocation of tasks between threads and available devices (multiprocessor CPUs and Intel Xeon Phi co-processors). The results of calculations of efficiency and acceleration are presented, a comparative analysis of the developed parallel implementations is made. The comparison of implementations with each other and with commercial counterparts on the efficiency of memory usage and processing time is shown. The use of parallel computations made it possible to accelerate the algorithm by up to 34 times, making the implementation of an algorithm comparable to commercial analogs. The calculations were carried out on the HybriLIT heterogeneous cluster of the Laboratory of Information Technologies of JINR.

In addition, algorithmic optimization of the reconstruction algorithm was carried out, allowing to minimize memory usage and reduce the number of calculations from $O(N^4)$ to $O(N^{3.5})$, and the Instarecon algorithm was implemented that reduces the complexity of reconstruction to $O(N^3 * \log(N))$. Work is under way to improve the quality of reconstruction using fast algorithms.

In order to tackle applied problems, software was developed for the segmentation of volumetric images of spectral tomography and subsequent granulometric analysis, allowing to calculate such quantities as volume, surface area, average intensity (X-ray density), RMS of intensity, orientation, sphericity, etc.

The development of methods for spectral X-ray microtomography, an important advantage of which is the possibility of separation of substances, requires a detailed simulation of the transmission of X-rays through matter. To solve this problem, a program based on the Geant4 [22] software package was developed. The simulation of the microtomograph included modeling of the spectrum of the X-ray source, of the radiation passage through the sample under consideration (taking into account the dependence of the linear attenuation coefficient on the energy of X-rays) and recording the obtained shadow image in a pixel detector. Since the Monte Carlo simulation of the microtomograph requires significant computational resources, the Amazon AWS cloud service was used for calcu-

[1]https://octopusimaging.eu

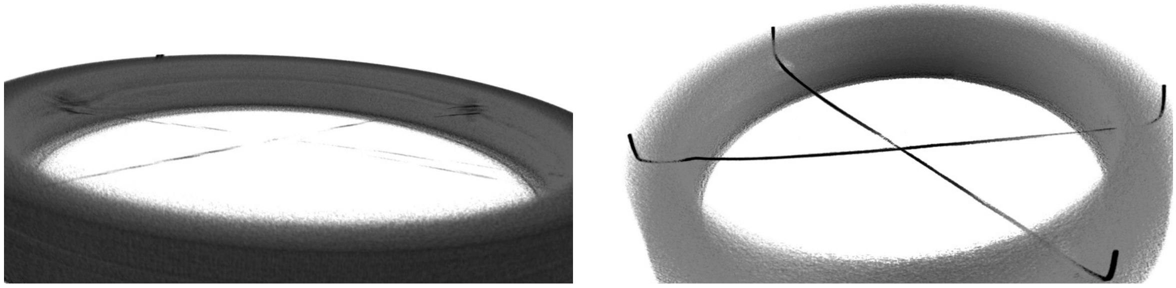


Figure 25: An example of the reconstructed image before (left) and after (right) alignment.

lations. Preliminary assessments of productivity and costs for modeling were performed depending on the instance type. It has been shown that the use of more expensive instances does not lead to a significant reduction in computation time. This feature can be explained by the fact that applications based on the Geant4 software package have extremely low efficiency of resource utilization on compute nodes with multi-core CPUs. It should be noted that the developed methods and software can be used for modeling by the Monte Carlo method in investigations of other nuclear-physical problems.

In addition, a procedure for mechanical alignment of the microtomograph was developed that resulted in a significant improvement of the quality of the obtained images (Figure 25). The procedure was repeatedly applied when changing the detector or the X-ray source.

3.3 Development program for 2018-2020

3.3.1 Site for characterisation of hybrid pixel detectors

The main improvement on the site for studying characteristics of pixel detectors is the creation of a deep-level relaxation spectroscopy (DLTS) station and mastering of the technique.

In addition, upgrades to the existing stations are planned: improvement of the power supply system of the "Kalan" station and installation of a high-voltage connection to the probe station, that will allow to measure capacitance-voltage characteristics at high bias voltage.

To carry out measurements with Timepix detectors, in particular on accelerators, several units of low-speed readout electronics are required.

3.3.2 Site for microtomography

The main difficulty in scanning with the MARS microtomograph is the long scanning time of large samples. First of all, this is due to the small size of the detector in the installed camera (at present the camera contains one Medipix detector covering an area of 14 mm $\times$ 14 mm). In connection with this, during the course of the Project, it is planned to improve the microtomograph camera, in particular, to install one or two Quad detectors (i.e., consisting of 4 Medipix chips) in the microtomograph. Also, because of the X-ray tube deterioration, it will be necessary to replace the X-ray source in the tomograph within the next two years.

Experience with the MARS microtomograph showed that for a number of tasks the spatial resolution of $\sim$ 50 μm is not enough. First of all, this concerns the study of the fine structure of the wall of atherosclerotic plaques and the study of the porosity of oil and gas cores. In connection with this, the creation of another microtomograph with a fixed detector and a rotating sample, capable of achieving a spatial resolution of 5-7 μm due to geometric magnification, is planned on the microtomography site. To achieve a better image quality, a Hamamatsu X-ray source with a focal spot size of 15 μm and a Lambda Double-Hexa detector, to be produced within the framework of the GALAPAD-2 project, will be used in the second microtomograph.

The development of software for modeling and reconstruction of tomograms will continue. Particular attention will be paid to improving the quality of images, the use of fast algorithms for processing large volumes of tomographic data and using new hardware capabilities (multi-core processors, graphics accelerators, etc.).

3.3.3 Development of readout electronics based on the Medipix4 chip

In 2016, the Medipix-4 collaboration was created, which currently includes the Berkeley National Laboratory, CEA, CERN, the Czech Technical University, DESY, the Diamond Light Source, JINR, NIKHEF, the universities of Houston, Canterbury and Maastricht. The main goal of the collaboration is the development of a new generation of microcircuits of the Medipix family, based on the technological process of 65 nm. Two chips will be developed simultaneously: Medipix4 and Timepix4. The key characteristics of the new microcircuits are presented in Table 3.1.

Thanks to the use of the TSV (Through-Silicon-Via) technology, the Medipix4 chip will be the first chip that can be tiled on 4-sides, which will make posible creation of large area detectors with no dead zones. In addition, the chip can be adapted to sensors with different pixel pitch, in accordance with the material requirements of the selected sensor and the target X-ray energy range. The Timepix4 chip will measure the acquisition time

	Medipix4	Timepix4
Pixel size	50 μm	35 μm
Polarity of the collected charge	$\pm$	$\pm$
Noise level	$\leq 75e^-$ rms (SPM)	$\leq 75e^-$ rms
Signal conditioning time	25 ns, 50 ns, 100 ns	–
Tileability	4-side	3-side
Timestamp accuracy	–	$<$ 1 ns
Number of thresholds	4,16	–

Table 3.1: Key features of the Medipix-4 and Timepix-4 chips.

of particles with an accuracy of 1 ns or better, on a pixel matrix with an extremely small pitch. It should be noted that some characteristics can be changed in the development process, as a result of the changing requirements of the Medipix-4 collaboration or as a result of technological limitations at the development stage.

Since JINR is a full-fledged participant in the Medipix-4 collaboration who have access to both experimental chips and scientific and technical documentation on their use, it seems quite natural to prepare in advance for the development of future application based on the new chips. First of all, this concerns the development of the technology of mounting the microcircuits on chipboards and the development of readout electronics.

Although mounting of Timepix4 chips will be carried out by the already known and mastered method of ultrasonic micro-welding, the application of the TSV technology in the Medipix4 chips requires a development of soldering by the BGA method. In this regard, during the implementation of the Project in 2018-2020, it is planned to purchase an installation for BGA-mounting and investigation of optimal modes for soldering with beads.

During the course of the Project in 2016-2017, a proprietary prototype of the readout electronics was developed for the Medipix family of detectors, which consists of an Altera Cyclone 5 SoC FPGA board and an adapter board with a VHDCI connector (Figure 26). For this prototype software was developed: firmware for the both FPGA and processor and graphical interface for PC. Data transfer to the PC is carried out via Ethernet. The conversion of the pseudo-random counting of the detector is performed in the FPGA. Data from the detector is stored in a shift register (3584 bits - string). As the register is filled, the data is converted from a pseudo-random form to a regular one by one pixel (14 bits). The finished data remains in the FPGA memory, from where it is read out by the processor and transmitted to the PC.

In 2018-2020, it is planned to create a full-featured readout electronics unit, focused on

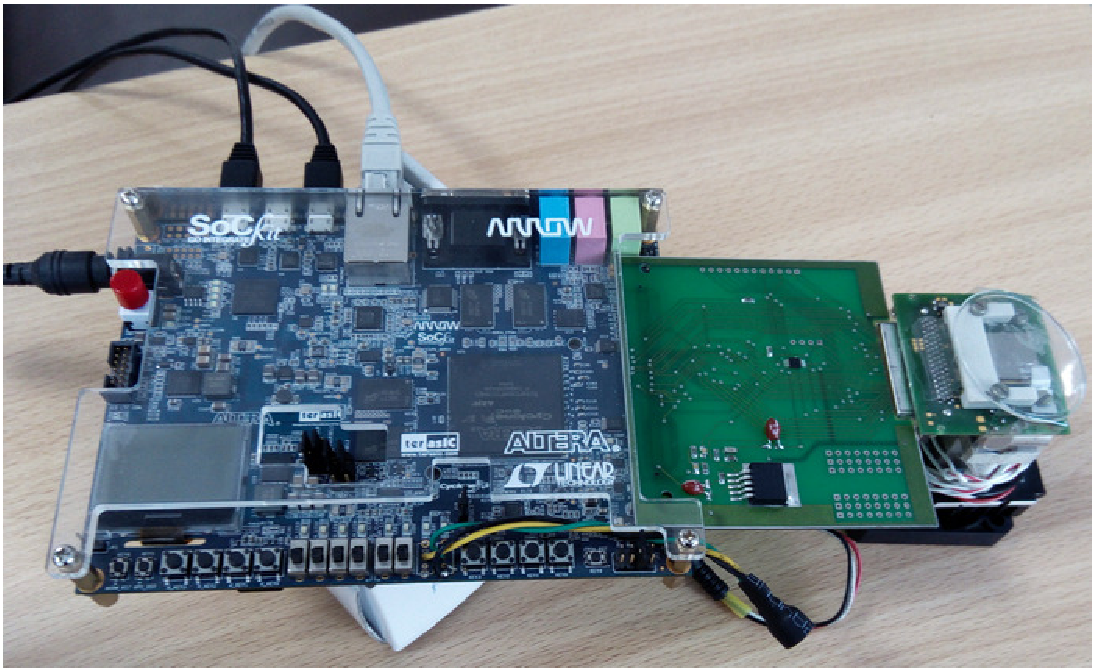


Figure 26: The prototype of the readout electronics unit for the Medipix family detector.

low-speed data retrieval from the Medipix4 chip and development of technical solutions for high-speed data acquisition and simultaneous readout of data from several (up to 8) chips on prototypes.

Chapter 4

Applied research

Applied research under the proposed Project will be conducted in collaboration with scientific groups from other research centers in order to study the feasibility of using the developed detectors and technologies in other areas of science and technology (primarily in the fields of medicine and geology), in particular the MARS microtomograph. The list of research centers with which scientific and technical cooperation is established is given in section 6.3.

4.1 Main results in 2015-2017

4.1.1 Investigation of roentgen contrast substances. Studies of possibility of identifying contrast agents by spectral information.

Studies of the identification of contrast agents were carried out on a phantom containing an aqueous solution of gold chloride (gold concentration 2 and 8 mg/ml), an aqueous solution of $CaCl_2$ (calcium concentration 240 mg/ml), an aqueous solution of MultiHance (gadolinium concentration 2 and 8 mg/ml), Omnipaque 300 aqueous solution (iodine concentration 18 mg/ml), as well as distilled water and vegetable oil. Scanning was carried out on three detectors:

1. GaAs 500 μm with Medipix3.1 chip - does not allow to measure the dependence of the linear attenuation coefficient (LAC) on energy due to very poor energy resolution related to some problems in Medipix 3.1 electronics,

2. GaAs 1000 μm with Timepix chip,

3. GaAs 300 μm with Timepix chip.

Absorption curves allow identification of various substances, if they are aggregated in large clusters. A program has been developed that allows to segment an image based on energy information and to plot absorption curves for each segment (Figure 27). The obtained curves can be correlated with the absorption curves for the reference samples (Figure 28).

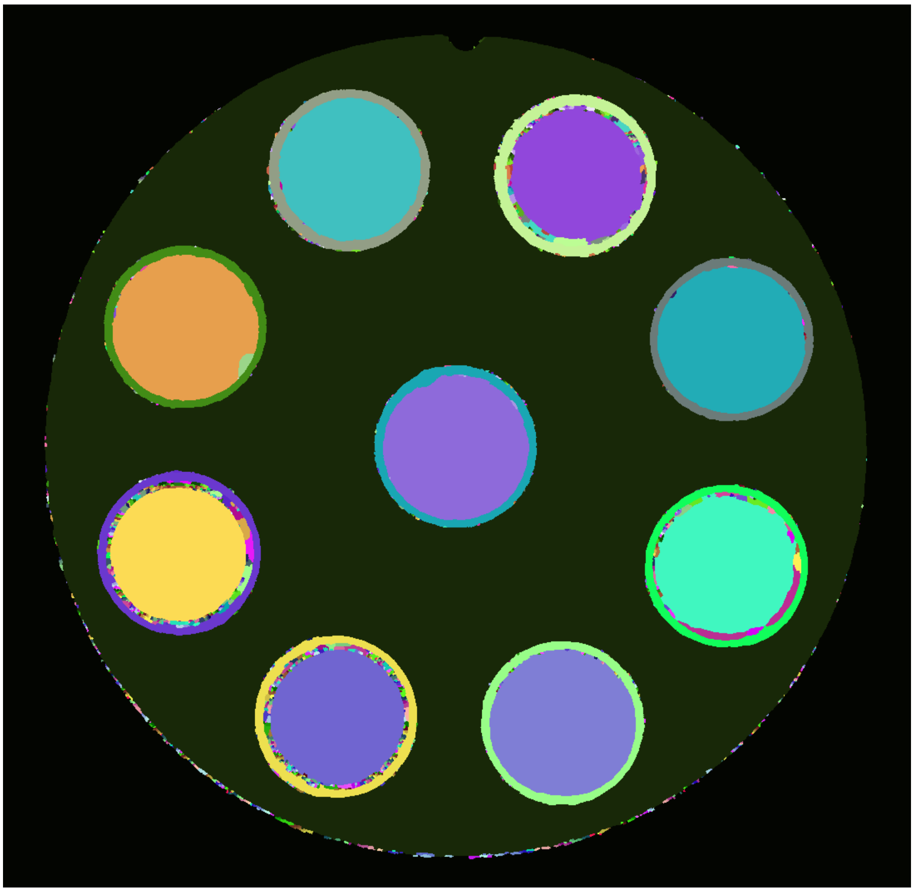


Figure 27: Segmented cross-section of phantom for 9 thresholds.

4.1.2 Investigation of native specimens for analysis of atherosclerotic vascular damage

A study was made of the micro and macrostructure of two specimens of atherosclerotic plaques in human carotid arteries obtained during endarterectomy operations. The study of ex vivo specimens is aimed at the study of the roentgenological structure of atherosclerotic plaques, which until recently was impossible because of insufficient resolution of usual CT methods. The data on plaque structure and the size and the form of microcalcinates (Figure 29) were obtained.

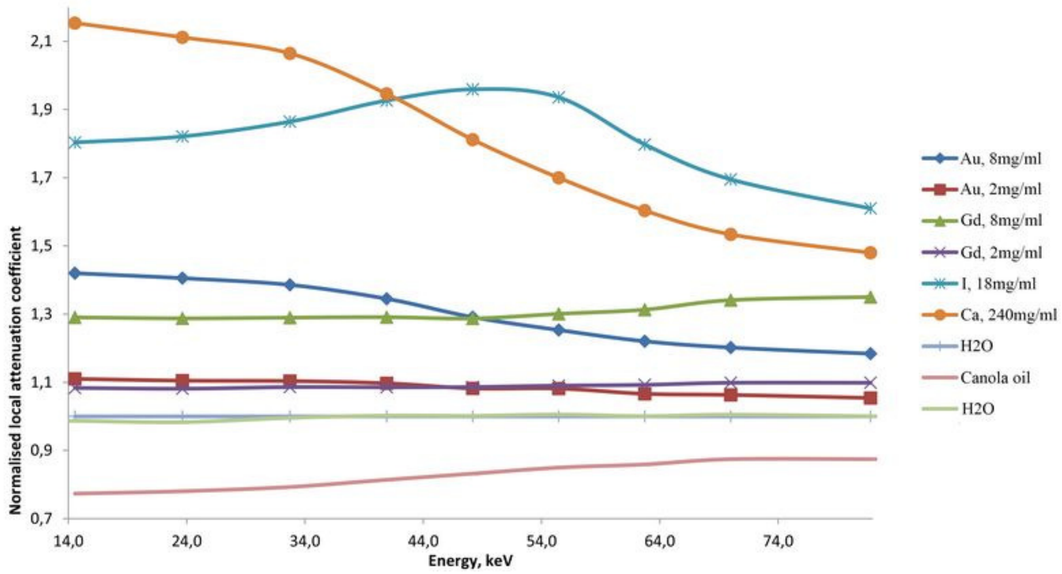


Figure 28: Dependence of linear attenuation coefficient on energy for various substances (normalized to water).

4.1.3 Investigation of native specimens for analysis of abdominal aortic aneurysms

A study was made of the micro and macrostructure of more than 10 specimens of aneurysm of abdominal aorta. The scan results showed the presence of microcalcinates in all specimens from large aggregates of calcinates to small ones, about 100 microns in size (Figure 30). An additional study using a Raman microscope revealed the presence of calcinates of the order of a few micrometers in size. These data allow to quantify the effect of dense formations on the strength of the vessel wall and, in the future, may lead to development of a method for predicting the probability of rupture of an aneurysm.

4.1.4 Analysis of composition of ores and minerals

For the reproduction of mineral resources, reliable estimates of reserves, the geological justification of the optimal regime for developing deposits, and the development of innovative technologies for their processing, it is now necessary to thoroughly study the material composition and morphostructural parameters of natural and man-made raw materials. Such studies allow to obtain the most complete and reliable information on the mineral composition that determines the quality of raw materials, features, characteristics and behavior of mineral phases in technological processes. It is important to have technologies that allow to make a predictable assessment of the quality of raw materials

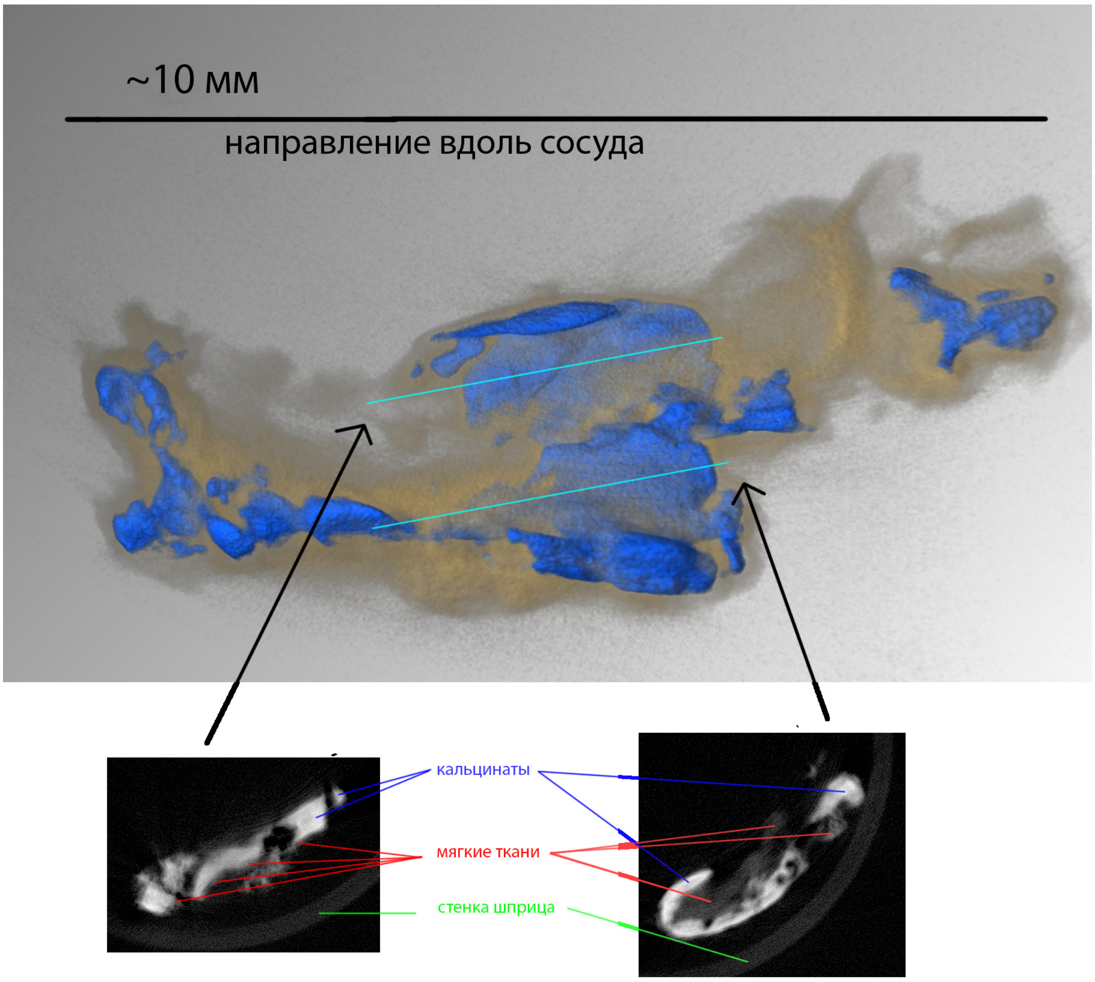


Figure 29: Tomographic image of an atherosclerotic plaque in human carotid artery. Blue color shows microcalcinates.

promptly and economically.

During the scanning of several samples of ores and minerals on the MARS microtomograph, it was shown that it is possible to obtain data on the morphostructural features of the mineral substance, by which it is possible to predict the quality, technological properties of the raw materials and their behavior in the technological processing. In particular, the study of samples of manganese ore showed the possibility of easy separation of chromite grains and determination of their characteristics (size, quantity, etc. - see Figure 31).

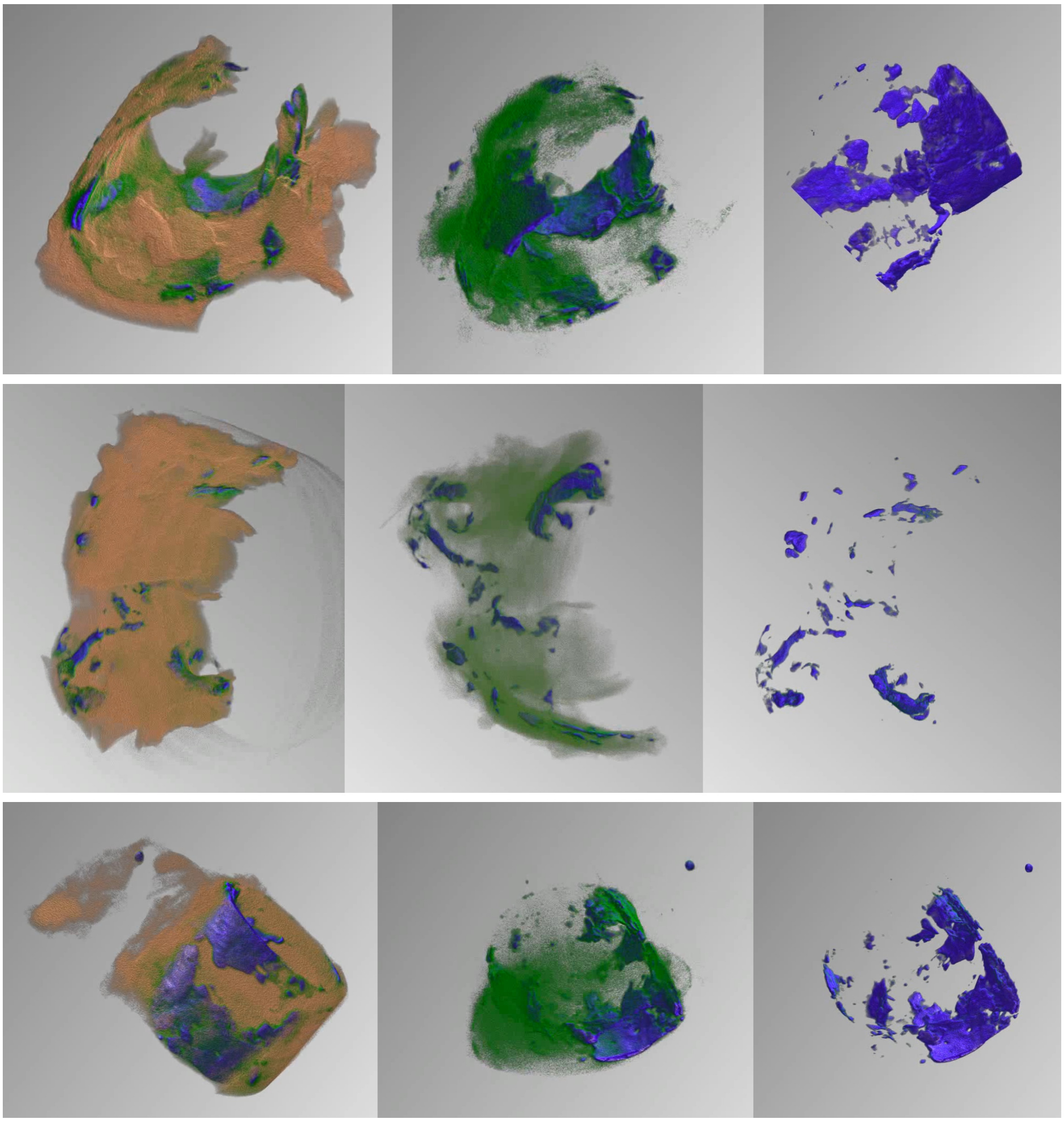


Figure 30: Tomographic images of abdominal aortic aneurysm specimens. Blue color shows microcalcinates, yellow – soft tissues, green – denser tissues.

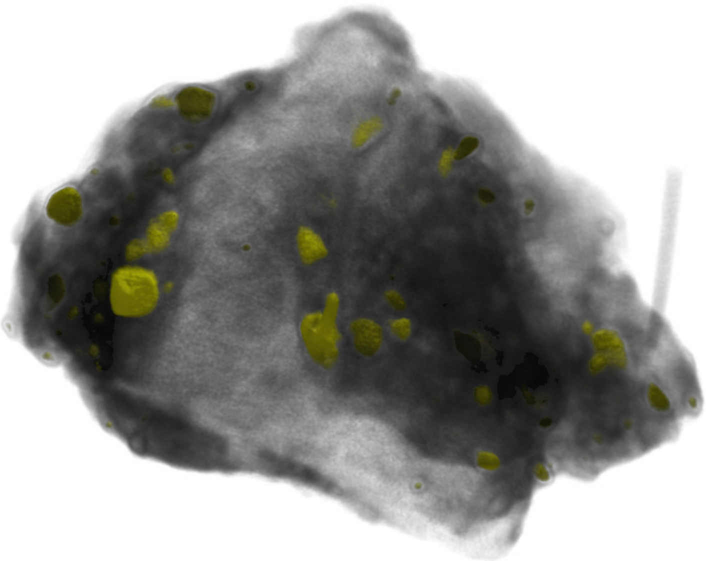


Figure 31: Chromites in manganese ore.

4.1.5 Investigation of core of oil and gas bearing rocks

Trial scans have shown the ability to identify representative areas of a full-length core, but now the measurement of 1 cm of length takes about 10 hours, that is not suitable for serial measurements. However, this does not exclude the use of microtomography with gallium arsenide detectors based on the Medipix chip for serial measurements, provided that the design of the tomograph is refined.

Conducting quantitative measurements of porosity on small samples turned out to be inexpedient because of the MARS microtomograph insufficient spatial resolution of 50 μm, while resolution of better than 10 μm is required.

4.2 Research program for 2018-2020

In the framework of the Project over the next three years, it is planned to carry out applied research in the following areas.

1. Investigation of the fine structure of calcium deposits on the walls of atherosclerotically affected carotid arteries and aortic aneurysms. The point is that calcium deposits can be a) a thin microcellular structure that indicates the strengthening

of the vascular tissue and b) coarse conglomerates that, on the contrary, can be associated with local inflammation, the formation of thrombi and contribute to the destruction of tissue elements. This makes it possible to predict the development of atherosclerotic vascular lesions.

2. Identification of adipose tissue of small animals. There is a problem of determining the amount of adipose tissue in laboratory animals, which complicates medical research related to obesity. Spectral microtomography makes it possible to isolate lipids by combining information on the density and the energy dependence of the linear attenuation coefficient.

3. Studies of the possibility of isolating radiopaque substances in the body according to the energy dependence of the linear attenuation coefficient. One possible application is to study drug delivery using radiopaque markers. Another possible application is the simultaneous detection of several roentgen contrast substances in the body.

4. Studies of the principle possibility of creating equipment based on Medipix detectors, suitable for use in clinical practice. Along with the diagnostic capabilities, an assessment will be made of parameters such as the scan time and the amount of absorbed dose depending on the image quality.

5. The ability of Timepix detectors to identify particle types and measure energy release opens up the prospect of using such detectors for measurements of the equivalent dose. During the implementation of the Project, the possibility of creating microdosimetric probes based on these detectors will be studied.

6. The study of ores and mineral raw materials will continue, the potential usage of spectral microtomography to identify the mineral phases will be studied.

The creation of another microtomograph with a higher spatial resolution (up to 5-7 microns) can significantly expand the range of problems to be investigated.

Chapter 5

Publications in 2015-2017

1. A. Butler, P. Butler, S. Bell, G.A. Chelkov, D.V. Dedovich, M.A. Demichev, V.G. Elkin, M.I. Gostkin, S.A. Kotov, D.A. Kozhevnikov, U.G. Kruchonak, A.A. Nozdrin, S.Yu. Porokhovoy, I.N. Potrap, P.I. Smolyanskiy, M.M. Zakhvatkin, A.S. Zhemchugov. Measurement of the Energy Resolution and Calibration of Hybrid Pixel Detectors with GaAs:Cr Sensor and Timepix Readout Chip. // Physics of Particles and Nuclei Letters, Vol. 12, No. 1, 2015

2. A.P. Butler, P.H. Butler, S.T. Bell, G. Chelkov, M. Demichev, A. Gongadze, S. Kotov, D. Kozhevnikov, U. Kruchonak, I. Potrap, A. Zhemchugov. Alignment and resolution studies of a MARS CT scanner // Particles and Nuclei Letters, Vol. 12, No. 1, 2015

3. FCAL collaboration. Performance of fully instrumented detector planes of the forward calorimeter of a Linear Collider detector // JINST 10 P05009, 2015

4. A. Guskov, G. Shelkov, P. Smolyanskiy, A. Zhemchugov. On the possibility to use semiconductive hybrid pixel detectors for study of radiation belt of the Earth. // J. Phys.: Conf. Ser. 675 032018, 2016

5. S.M. Abu Al Azm, G. Chelkov, D. Kozhevnikov, A. Guskov, A. Lapkin, A. Leyva Fabelo, P. Smolyanskiy and A. Zhemchugov. Response of Timepix Detector with GaAs:Cr and Si Sensor to Heavy Ions. // Physics of Particles and Nuclei Letters, Vol. 13, No. 3, pp. 363–369, 2016

6. P. Smolyanskiy, G. Chelkov, A.Guskov, D.Dedovich, D.Kozhevnikov, U.Kruchonak, A.Leyva, A.Zhemchugov. Characterization of GaAs:Cr-based Timepix detector using synchrotron radiation and charged particles, // J. Inst. 11, C12070, 2016

7. D. Kozhevnikov, G. Chelkov, M. Demichev, A. Gridin, P. Smolyanskiy, A. Zhemchugov. Performance and applications of GaAs:Cr-based Medipix detector in X-ray CT, // J. Inst. 12, C01005, 2017

8. Svetlikov A.V., Zhemchugov A.S., Kozhevnikov D.A., Gurevich V.S., Shelkov G.A., Khubulava G.G., Evaluation of human ruptured infrarenal aorta aneurysm by new high resolution microtomography // European Heart Journal, 37. (Suppl). 270. P.1477, 2016

9. Zhemchugov A., Svetlikov F., Kozhevnikov D., Shelkov G., Urazgildeeva S., Gurevich V., Usage of novel hybrid pixel detectors for native atherosclerotic plaque imaging by high resolution x-ray computed tomography // Atherosclerosis, 252. e215, 2016

10. Andriyashen V., Gerasimov A., Provorov A., Demichev M., Kozhevnikov D., Geant4-based simulation of a micro-CT scanner using cloud resources // Proceedings of the 7th International Conference "Distributed Computing and Grid-technologies in Science and Education (GRID 2016), Dubna, Russia. CEUR Workshop Proceedings (CEUR-WS.org), 2017, p.502-506

11. Tokareva V., Gridin A., Kozhevnikov D., Streltsova O., Zuev M., Parallel implementations of image reconstruction algorithms for X-ray microtomography // Proceedings of the 7th International Conference "Distributed Computing and Grid-technologies in Science and Education (GRID 2016), Dubna, Russia. CEUR Workshop Proceedings (CEUR-WS.org), 2017, p.481-485

Chapter 6

The Project implementation plan

6.1 Cost estimates for the Project

No	Expenditures	Total amount	2018	2019	2020
	Direct Project costs				
1	Materials	60	20	20	20
	gallium arsenide sensors	30	10	10	10
	reagents and electronics	30	10	10	10
2	Equipment	350	117	117	116
	testing stations	77	67	5	5
	microtomography site	180	30	90	60
	assembly site and development of readout electronics	33	0	2	31
	lab and measurements equipment	45	15	15	15
	computing equipment	15	5	5	5
3	R&D (preparations of materials etc.)	10	3	3	4
	Travel expenses	30	10	10	10
	a) countries of the non-ruble zone	24	8	8	8
	b) countries of the ruble zone	6	2	2	2
	Total direct costs:	450	150	150	150

Table 6.1: Cost estimates for the Project (kUSD).

6.2 List of equipment

During the implementation of the Project in 2018-2020, it is planned to purchase and install in the DLNP the following equipment.

- At the testing site:
    1. a crate with high-voltage and low-voltage power supplies for the "Kalan" testing station;
    2. low-speed readout electronics for Medipix detectors (Widepix or analogues);
    3. high-voltage connection for CV measurements at the probe station;
    4. installation for DLTS measurements.
- At the microtomography site:
    1. compact microfocus X-ray source - 2 pcs;
    2. high-speed readout electronics for Medipix detectors (LAMBDA or SPIDER) - 2 pcs;
    3. mechanical and positioning parts for a new microtomograph.
- At the assembly site:
    1. installation for testing of Medipix4 chips;
    2. installation for BGA-assembly.

To achieve the Project goals, it will also be necessary to purchase common laboratory and measuring equipment: power supplies, oscilloscopes, etc.

In addition, it is planned to purchase licensed software for FPGA programming and wiring of printed circuit boards, as well as computer equipment (portable PCs for test beam sessions on accelerators and a high-performance server for the reconstruction of microtomograms).

6.3 Scientific cooperation

The research within the framework of the Project will be carried out in cooperation with the following countries and international organizations:

Germany

- DESY, Hamburg, Zeuthen

Cuba

- Center of Technological Applications and Nuclear Development (CEADEN), Havana

New Zealand

- University of Otago, Christchurch

Russia

- National Research Tomsk State University, Research and Education Center for Physics and Electronics of compound semiconductors, Tomsk
- St. Petersburg State University, Faculty of Medicine, Institute of Advanced Medical Technologies, Scientific Clinical Cardiology and Education Center, Department of atherosclerosis, St. Petersburg
- Mechnikov Northwestern State Medical University, St. Petersburg
- Federal State Institution of Health Sokolov Clinical Hospital № 122 of the Federal Medical-Biological Agency of the Health Ministry, Centre for Vascular Surgery, St. Petersburg
- Moscow State University, Faculty of Fundamental Medicine, Moscow
- International University of Nature, Society and Man, Dubna
- Petrovsky Russian Research Center of Surgery of the Russian Academy of Medical Sciences

Romania

- Institute for Space Research, Bucharest

Czech Republic

- Czech Technical University in Prague, Institute of Experimental and Applied Physics, Prague

Switzerland

- European Organization for Nuclear Research (CERN), Geneva

Bibliography

[1] URL: http://www.linearcollider.org

[2] URL: http://clic-study.web.cern.ch

[3] URL: http://www.cern.ch/HL-LHC

[4] URL: http://www.xfel.eu

[5] URL: http://www.eli-laser.eu/

[6] URL: http://cordis.europa.eu/esfri/

[7] ATLAS Collaboration, "Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment" // CERN-2012-022/LHCC-I-023 January, 2013

[8] G. Lindström, M. Moll and E. Fretwurst, "Radiation hardness of silicon detectors — a challenge from high-energy physics" // Nucl. Instrum. Meth. A 426 (1999) 1

[9] RD8 collaboration, R.L. Bates et al., "The effects of radiation on gallium arsenide radiation detectors" // Nucl. Instrum. Meth. A 395 (1997) 54.

[10] V. Chmill, "Radiation tests of semiconductor detectors" // Ph.D. Thesis, Stockholm Sweden (2006)

[11] T. Ly Anh, A. Perd'ochov'a, V. Nečas and V. Pavlicoѵá, "Radiation resistance study of semi-insulating GaAs-based radiation detectors to extremely high gamma doses" // Nucl. Phys. Proc. Suppl. B 150 (2006) 402.

[12] A. V. Tyazhev et al., "GaAs radiation imaging detectors with an active layer thickness up to 1 mm" // Nucl. Instrum. and Meth. A509 (2003) 34–39

[13] K.Afanaciev et al., "Investigation of the radiation hardness of GaAs sensors in an electron beam" // JINST 7 (2012) P11022

[14] P. Kraft et al. “Performance of single-photon-counting PILATUS detector modules” // J. Synchrotron Radiat. 16 (2009) 368

[15] P. Pangaud et al., “XPAD3: A new photon counting chip for X-ray CT-scanner” // Nucl. Instrum. and Meth. A571 (2007) 321

[16] R. Ballabriga et al., “The Medipix3 prototype, a pixel readout chip working in single photon counting mode with improved spectrometric performance” // IEEE Trans. Nucl. Sci. 54 (2007) 1824

[17] H. Abramowicz et al., Instrumentation on the very forward region of a linear collider detector // IEEE Trans.Nucl.Sci., vol 51, year 2004, 2983:2989

[18] C. Coca et al., Expected electromagnetic and neutron doses for the BeamCal at ILD // Rom. J. Phys, vol. 55, numb. 7-8, (2010)687-707

[19] L. Tlustos, G. Shelkov, O. Tolbanov, “Characterisation of a GaAs:Cr Medipix2 hybrid pixel detector” // Nucl. Instrum. and Meth. A 633(2011) S103

[20] J. Jakubek, S. Pospisil, J. Uher “Neutron detector based on TimePix pixel device with micrometer spatial resolution” // Proc. SPIE 7449, Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XI, 744910 (September 11, 2009)

[21] Zainon, R. et al., “Construction and Operation of the MARS-CT Scanner” // Bandung, Indonesia: International Conference on Instrumentation, Control and Automation (ICA 2009), 20-22 Oct 2009.

[22] S. Agostinelli et al. [GEANT4 Collaboration], “GEANT4: A Simulation toolkit” // Nucl. Instrum. Meth. A 506 (2003) 250.

[23] U. Lachish, Electron lifetime determination in semiconductor gamma detector arrays // arxiv:1701.03459

[24] J. Jakubek et al.Neutron imaging with Medipix-2 chip and a coated sensor // Nucl.Instrum.Meth. A560 (2006) 143-147

[25] J. Bouchami et al. Estimate of the neutron fields in ATLAS based on ATLAS-MPX detectors data Neutron imaging with Medipix-2 chip and a coated sensor // JINST 6 (2011) C01042

[26] D. Dedovich et al. Proposal to Measure Radiation Field Characteristics, Luminosity and Induced Radioactivity in ATLAS with TIMEPIX detectors having GaAs:Cr sensors : Project GaAsPix // ATLAS Note ATL-COM-GEN-2016-001

[27] Granja C., Jakubek J., Koster U., Platkevic M., Pospisil S. Response of the pixel detector Timepix to heavy ions // Nucl. Inst. and Meth. A. 2011, V.633, P.155-158.

[28] Hoang S., Vilalta R., Pinsky L., Kroupa M., Stoffle N., Idarraga J. Data Analysis of Tracks of Heavy Ion Particles in Timepix Detector // J. Phys.: Conf. Ser., 2014, V.523, P.012026