Novel semiconductor detectors for fundamental and applied research

Project report and proposal for prolongation

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Motivation for the project and its goals

Motivation

- Planned detectors of the future accelerators (ILC, CLIC, HL-LHC, the muon collider, etc) require semiconductor detectors with considerably improved characteristics than today's detectors: higher readout speed, better granularity, cheaper production cost, and, particularly, very high radiation hardness up to a MGy scale.
- Applied research at the newly built and planned light sources (PETRA-III, XFEL, DLS, etc) require new generation of photon imaging detectors with higher resolution and sensitivity, low noise, capable of measuring photon energy.
- Despite many R&D in the scope of current experiments, for the moment there are no any generic detector R&D projects at DLNP (and very few at JINR), that are aimed to meet the requirements of tomorrow.

Goals

- Generic R&D of semiconductor radiation-resistant detectors based on new materials and generic R&D of hybrid pixel detectors with high spatial resolution for nuclear and particle physics and photon imaging.
- Development of infrastructure for characterization of semiconductor detectors, coupled with beam tests at the JINR facilities.
- Collaboration with research groups from other fields in feasibility studies of applying the newly developed detectors in various areas of science and technology.

Main Project deliverables and their accomplishment in 2014-2017

- ✓ Systematic study of the radiation hardness of GaAs:Cr-based detectors with beams of neutrons, γ-rays, electrons and charged hadrons.
- ✓ Production, in cooperation with DESY, of 50 GaAs:Cr sensors in HEXA topology (28×42 mm^2, 20M pixel in total) to be used at the beamlines of XFEL and PETRA-III.
- ✓ Producton of a prototype of hybrid pixel detector with a thick (≥ 1 mm) GaAs:Cr sensor and investigation of its characteristics.
- ✓ Production of prototypes of hybrid pixel detectors for detecting neutrons and fission fragments and development of particle identification methods by analyzing cluster shapes.
- ✓ Comparison of radiation hardness of Si and GaAs:Cr sensors at high energy electron beam and participation in the manufacturing and testing of the first module of the FCAL calorimeter.
- ✗ Production of a prototype of the low-background Timepix detector based on GaAs:Cr for TGV-2 experiment.
- ✗ Production of a prototype of a tracking hodoscope based on Timepix detectors to study relativistic hypernuclei decays.

Project realization: semiconductor radiation-resistant detectors

2015

- ✓ Radiation hardness studies of GaAs:Cr sensors to high fluence of neutrons on IBR-2M.
- ✓ Comparative measurements of radiation hardness of Si and GaAs:Cr sensors on the beam of high energy electrons in SLAC for FCAL.

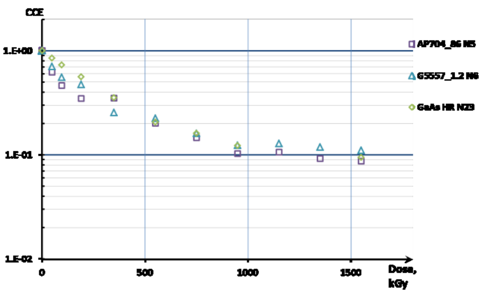
2016

- ✓ Creation of a new charge collection efficiency measuring station and systematic comparative studies of radiation hardness of two types of GaAs:Cr and Si sensors on the beams of JINR facilities (LINAC-200 and IBR-2M).

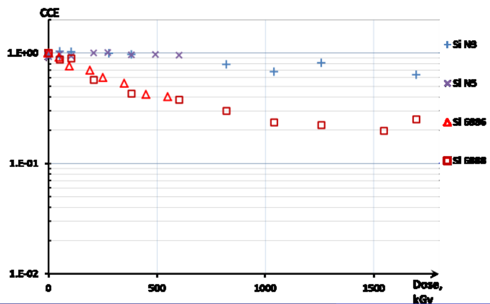
2017

- ✓ Comparative studies of radiation hardness of two types of GaAs:Cr and Si sensors to medium fluence of neutrons on IBR-2.

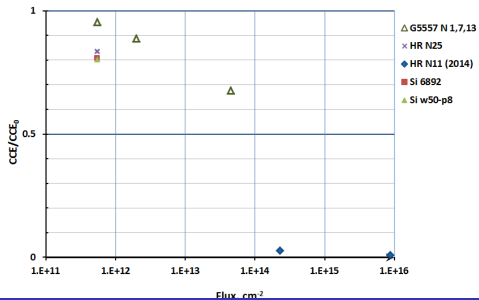
CCE vs dose (20 MeV e, GaAs:Cr)



CCE vs dose (20 MeV e, Si)



CCE vs n flux (GaAs:Cr and Si)



Project realization: hybrid pixel detectors

2015

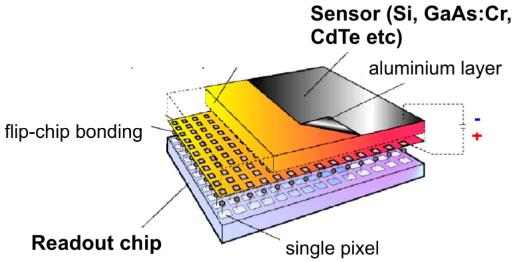
- ✓ Production of prototypes of Timepix hybrid pixel detectors with GaAs sensor of < 1 mm thickness. Study of their capabilities in detecting neutrons, fission fragments and charged tracks using JINR basic facilities (EG-5, Nuclotron, IBR-2M, U-400M).
- ✓ Production of 50 GaAs:Cr sensors in HEXA topology (with area 28×42 mm^2) to be used at the beamlines of XFEL and PETRA-III.
- ✗ Production of a prototype of GaAs-based hybrid pixel detector for TGV-2 experiment.
- ✓ Proposal to measure radiation field characteristics, luminosity and induced radioactivity in the ATLAS cavern with Timepix detectors having GaAs:Cr sensors (GaAsPix project).

2016

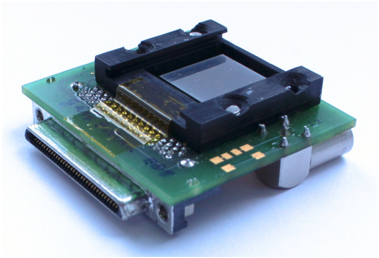
- ✓ Production of prototypes of GaAs-based pixel detectors of thickness $\geq$1 mm.
- ✓ Participation in the manufacture of the first module of the FCAL calorimeter.
- ✓ Development of methods and algorithms for the identification of neutrons and fission fragments in images from Timepix detectors.

2017

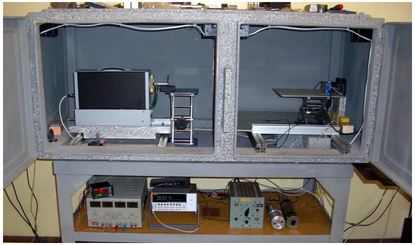
- ✓ Construction of a prototype of a neutron monitor based on Timepix detectors.
- ✗ Construction of a prototype of a tracking hodoscope for studying decays of relativistic hypernuclei.
- ✓ Installation of 10 GaAs:Cr Timepix detectors in the ATLAS cavern.



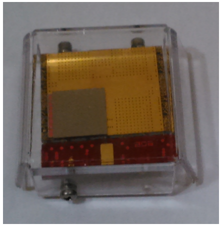
Hybrid pixel detector



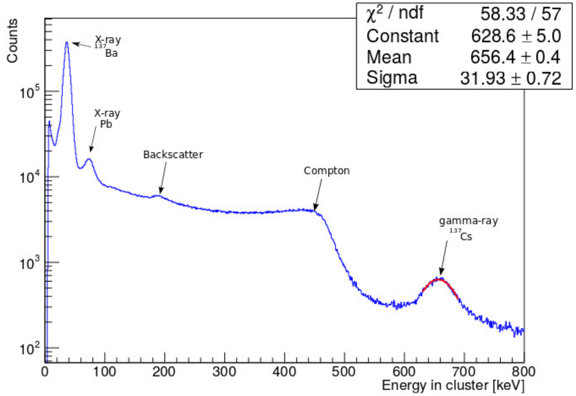
Timepix detector on carrier board



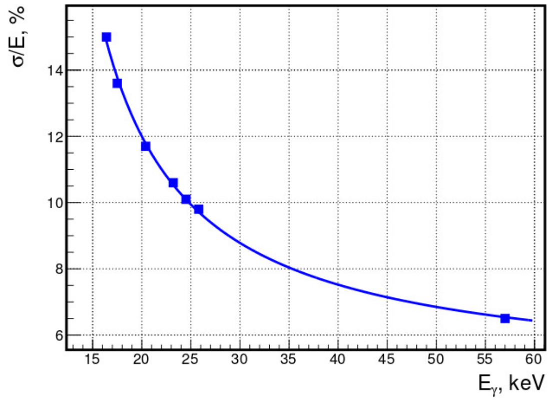
X-ray station for detector calibration



Quad module with 1mm thick Timepix detector



^{137}Cs spectrum after per-pixel calibration of 1mm thick Timepix detector

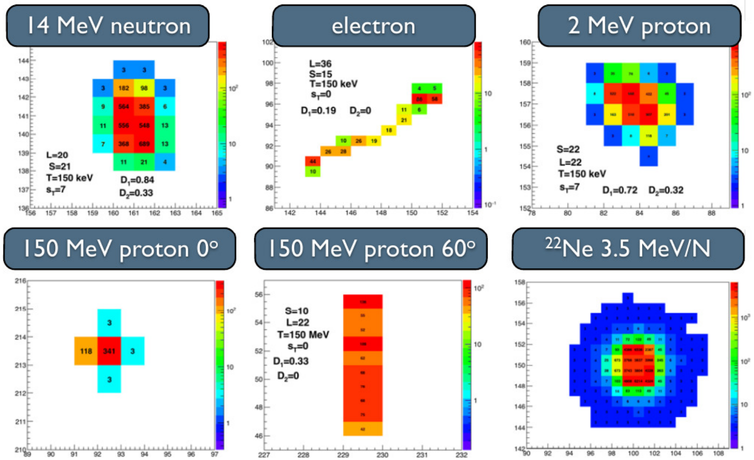


Energy resolution of 1mm thick Timepix detector

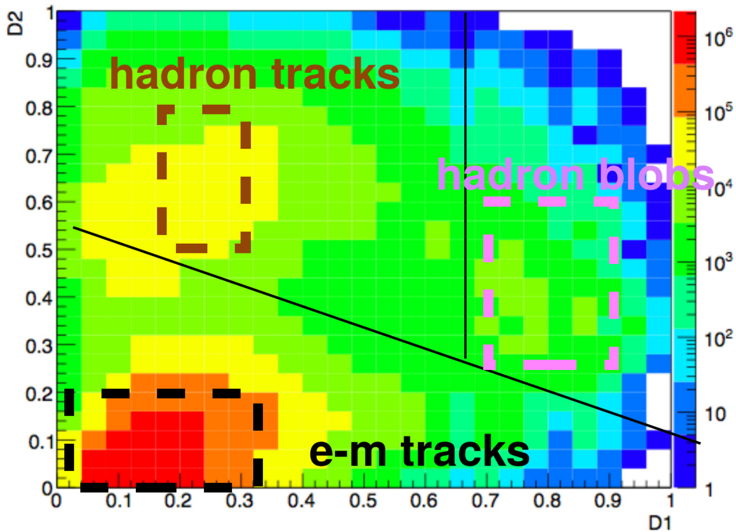
Some results in R&D of hybrid pixel detectors: particle identification

Separation of cluster types in Timepix detectors

- D1 – ratio of the cluster area to its perimeter, characterizes the cluster shape.
- D2 – ration of the number of pixels with energy release above a certain threshold to the total number of pixels in the cluster, characterizes the particle ionization losses.
- Plot of D2 vs D1 allows separate interactions of electromagnetic and nuclear nature.



Typical clusters formed in Timepix detectors



Project realization: infrastructure for characterization of detectors

2015

- ✓ Upgrade of the testing bench for detector characterization. Cleanroom refurbishment. Preparing the workspace for measuring irradiated samples.
- ✓ Installation of ultrasonic microwelding machine.

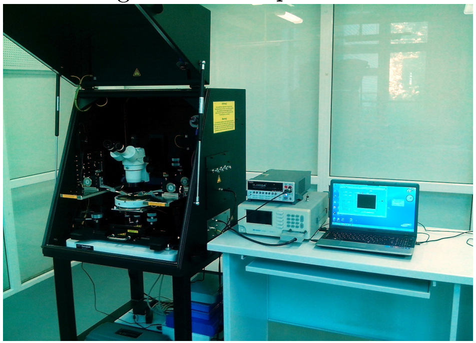
2016

- ✓ Mastering the skills of microwelding and mounting of detectors on carrier boards.
- ✓ New station for measuring charge collection efficiency.

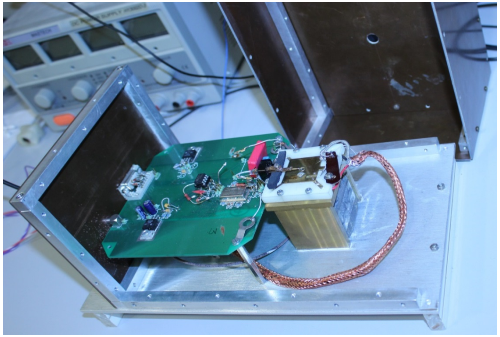
2017

- ✗ Equipment for technology of flip-chip bonding.

Testing bench with probe station



Station for CCE measurements



Ultrasonic microwelding machine

Project realization: applied studies with new detectors

2015

- ✓ Calibration of MARS-CT scanner and development of software for its control and data acquisition.
- ✓ Feasibility studies of identification of X-ray contrast media by spectral data.

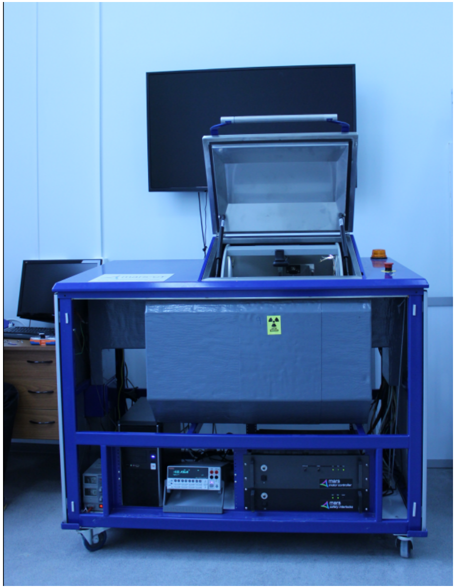
2016

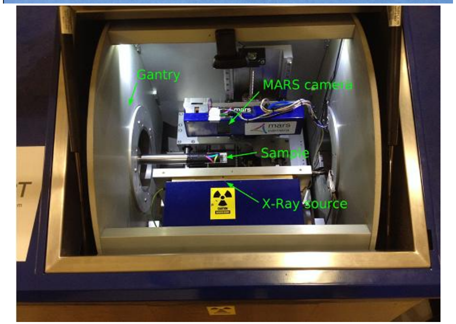
- ✓ Development of in-house software for CT image processing aimed at biological and geophysical studies.
- ✓ Investigation of native specimens for analysis of atherosclerotic vascular damage by micro-CT methods.
- ✓ Micro-CT analysis of composition of ores and minerals.
- ✓ Investigation of core samples of oil and gas bearing rocks.

2017

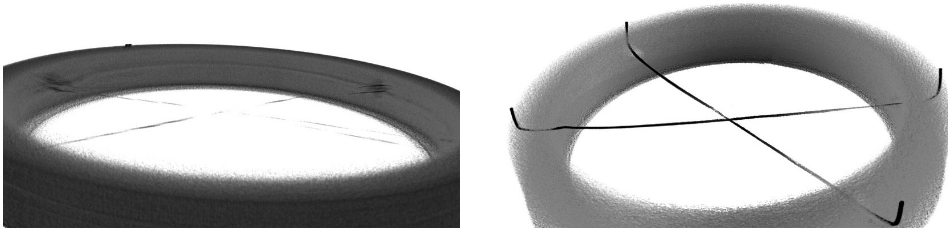
- ✓ Determination of the potential of spectral microtomography for identification of mineral phases in ores and minerals.
- ✗ Setting up a collective research center for studies with spectral microtomography.

Some results of applied studies: MARS CT-scanner improvements



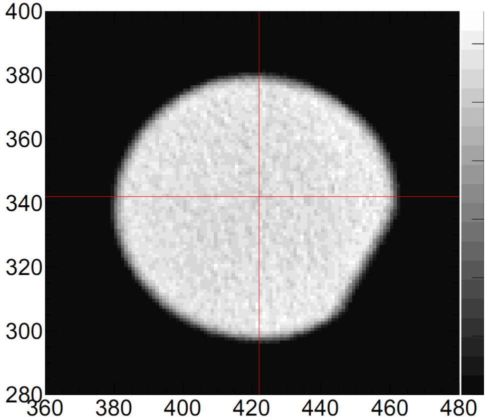


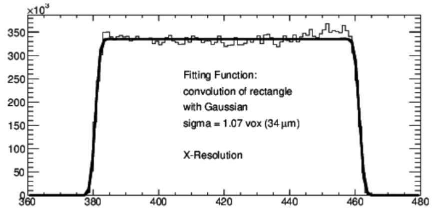
MARS CT-scanner

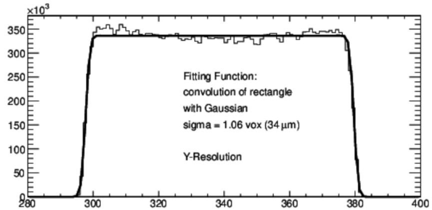


Reconstructed image of plastic ring with crossed W wires before (left) and after (right) alignment

Reconstuction of a 2.7 mm Al wire



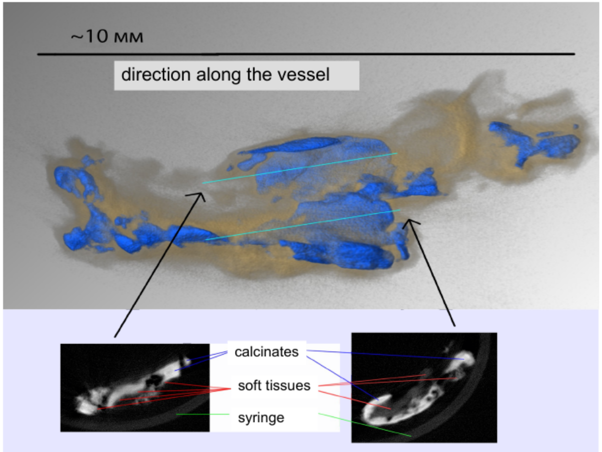




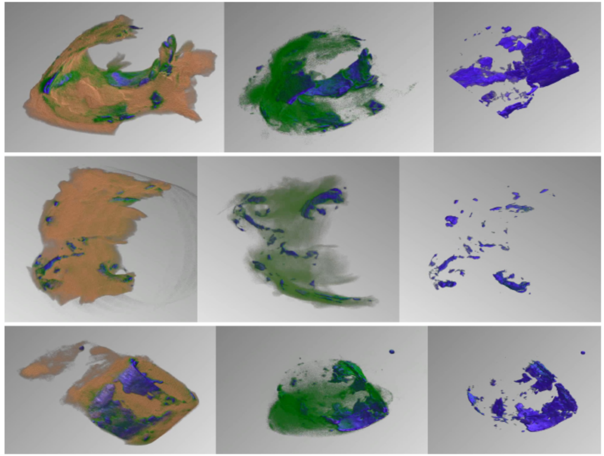
Achieved spatial resolution is 34 μm

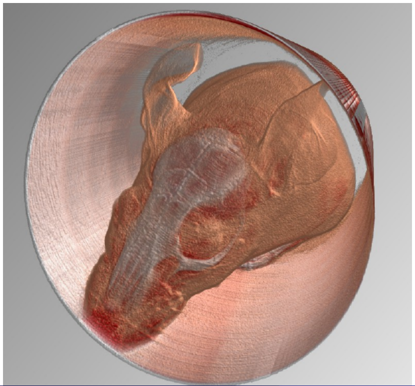
Some results of applied studies: biomedical

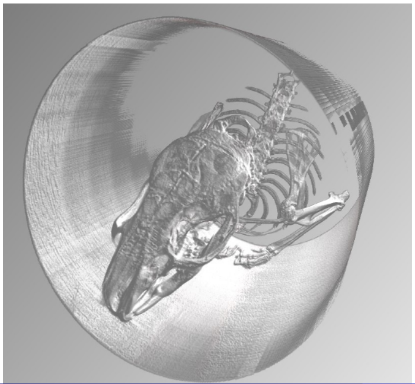
Atherosclerotic plaque in corotid artery

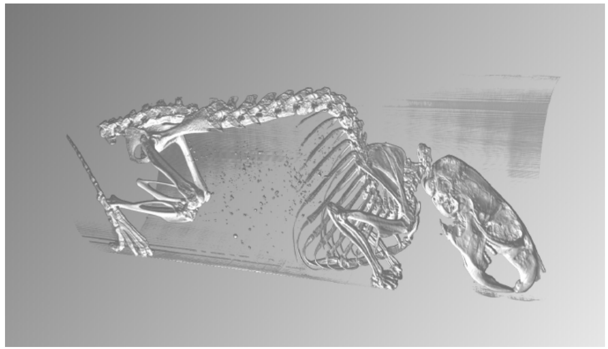


Abdominal aortic aneurysms



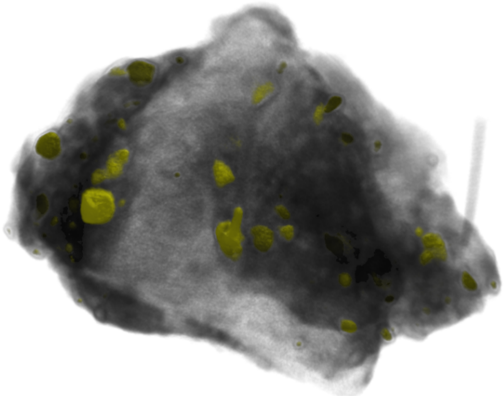




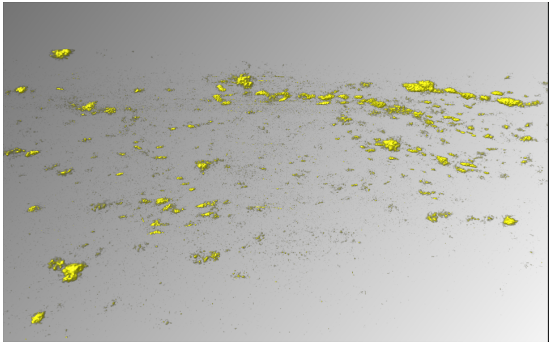


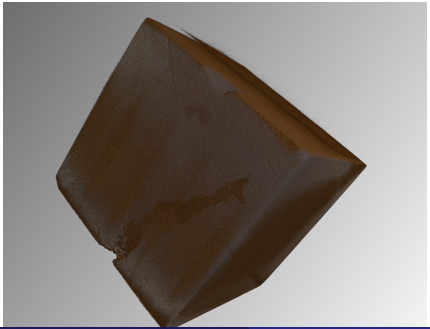
Some results of applied studies: geological

Magnetite (Fe_3O_4) rock enriched by inclusions of titanium minerals rutile, perovskite, etc (up to 20% of TiO_2)

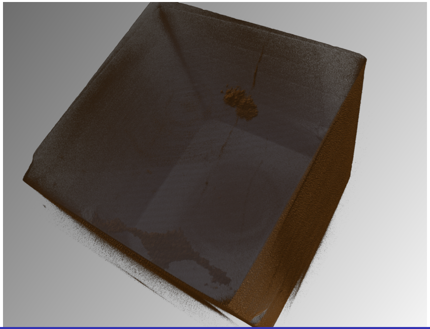


Chromespinellids (up to 35% of Cr_2O_3) inclusions in olivine ($(Mg,Fe)_2SiO_4$) rock



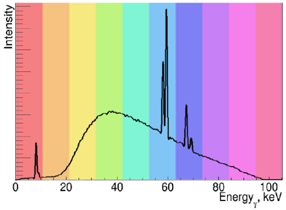


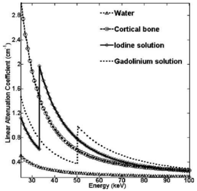
Cracks and pores in core sample of oil bearing rocks

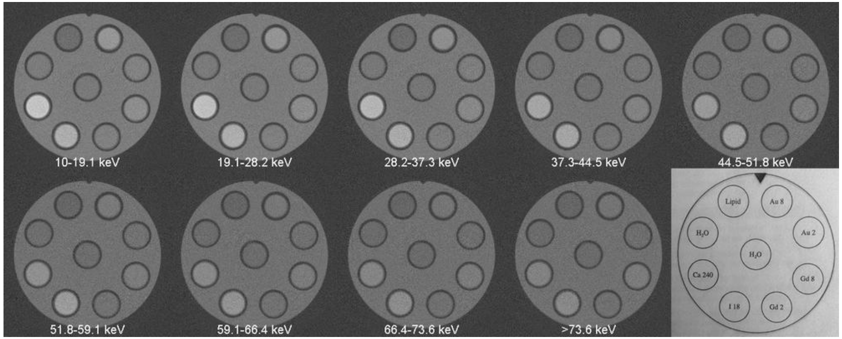


Video with 3D reconstructions

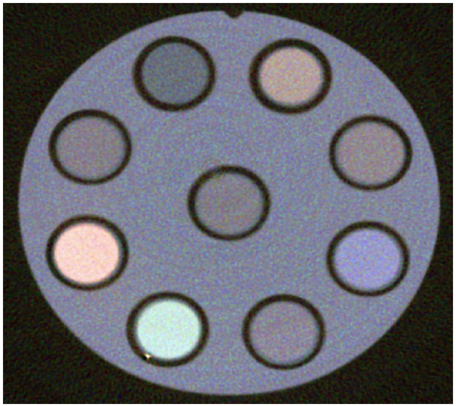
Some results of applied studies: spectarl CT

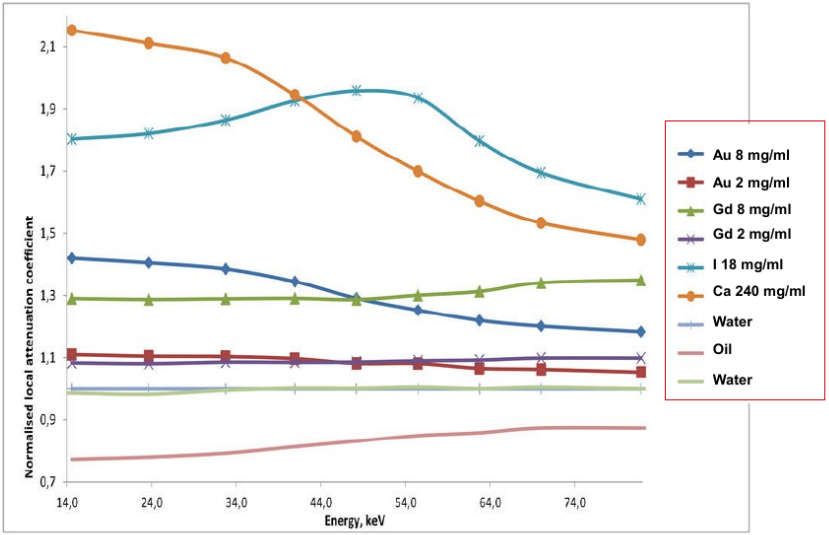




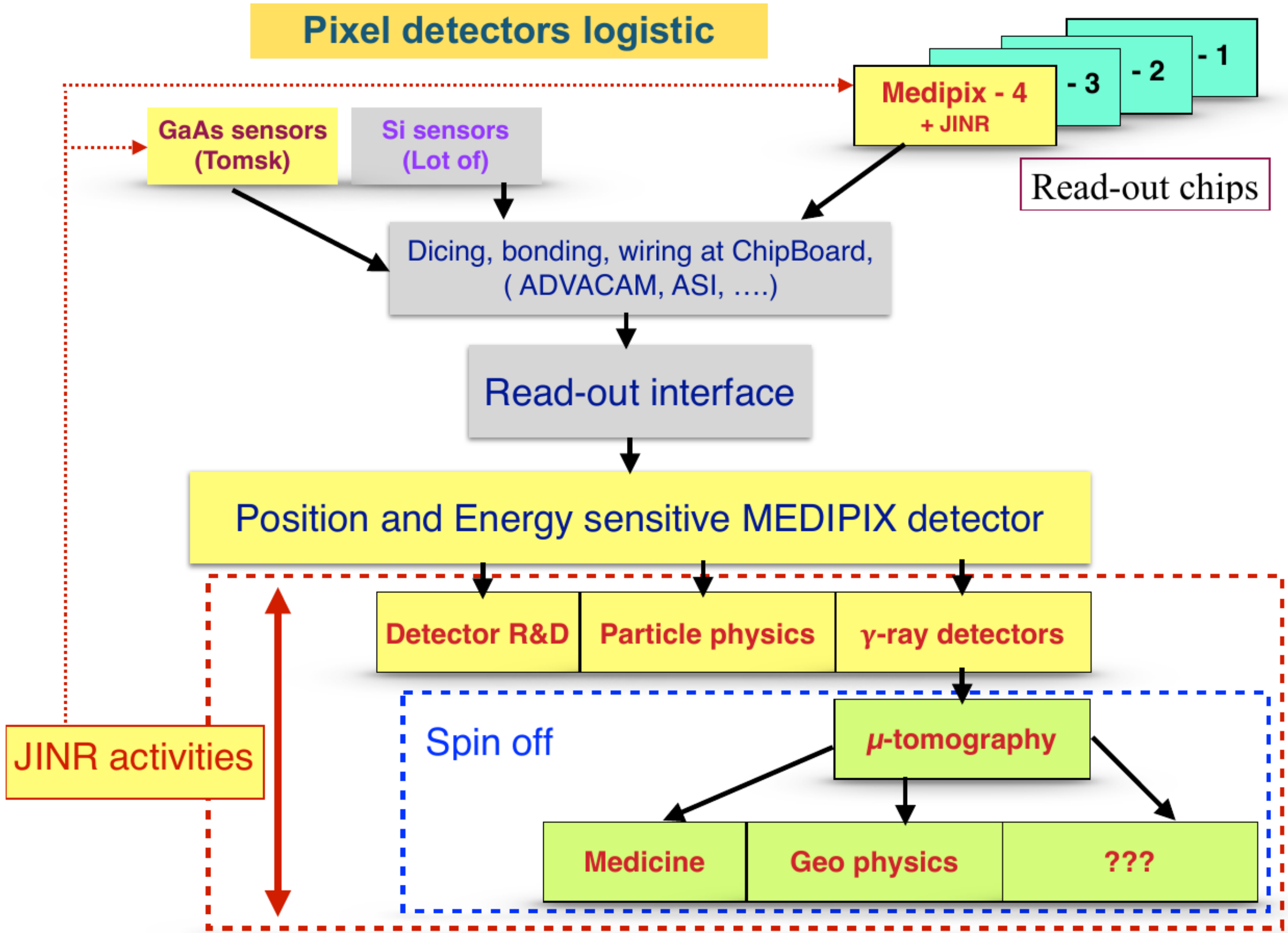


"True" colour X-ray CT





Hybrid pixel detectors workflow



List of publications in 2015-2017 (I)

Total of 12 publications:

- 6 related to X-ray computed tomography,
- 4 related to hybrid pixel detectors characterization and their applications,
- 1 about FCAL prototype and 1 patent application for hybrid pixel detectors.

Two more publications are almost ready for submission: about studies of GaAs:Cr radiation hardness and about GaAsPix project in ATLAS.

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”, Physics of 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

List of publications in 2015-2017 (II)

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", JINST 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", JINST 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
12. G. Chelkov, M. Demichev, S. Kotov, D. Kozhevnikov, U. Kruchonak, P. Smolyanskiy, A. Zhemchugov, "Semiconductor pixel detector of charged stronly ionizing particles (multiply charged ions)", Russian patent application №2016150633

Research program for prolongation of the Project

Program for R&D of semiconductor detectors in 2018-2020

- Searches for methods to increase the radiation hardness of gallium arsenide detectors:
  - introduction of new doping impurities that compensate for the effect of defects on charge collection,
  - station for carrying out measurements using methods of deep level transient spectroscopy (DLTS).
- Further development of algorithms for identification of particles in hybrid pixel detectors, including algorithms based on deep learining neural networks.
- Neutron registration and determination of the fast neutron spectrum by using converters with different neutron-induced thresholds.
- Accumulation of data from GaAsPix ATLAS system and its analysis.
- Studies of hybrid pixel detectors response to the passage of heavy charged particles:
  - development of reliable methods for measuring the energy and coordinates of particle interaction in the sensor,
  - development and verification of methods for determining characteristics (intensity, profile, particle composition) of heavy ion beams.
- Application of pixel detectors in experiments with hypernuclei and relativistic ions on the Nuclotron (a polarimeter based on the Timepix detector).

Expansion of research infrastructure in 2018-2020

- Site for characterisation of hybrid pixel detectors:
  - measuring station for deep-level relaxation spectroscopy (DLTS),
  - small upgrades to the existing stations (new power supplies, several units of low-speed readout electronics).
- Site for microtomography:
  - installation of Quad GaAs:Cr detectors (consisting of 4 Medipix chips) in the MARS CT-scanner,
  - replacement of the X-ray source in the MARS microtomograph,
  - creation of another microtomograph with a fixed large area detector (Double-Hexa topology) and a rotating sample, capable of achieving a spatial resolution of 5-7 μm.
- Development of readout electronics based on the Medipix4 chip:
  - installation for BGA-mounting of Medipix4 chips on carrier boards,
  - installation for testing of Medipix4 chips,
  - creation of a full-featured readout electronics unit, focused on low-speed data retrieval.

Program for applied studies in 2018-2020

- Development of spectral microtomography, including the improvement of computational methods both on the hardware and software sides.
- Investigation of the fine structure of calcium deposits on the walls of atherosclerotically affected carotid arteries and aortic aneurysms for prediction of potential dangers.
- Identification of adipose (fat) tissue of small animals by combining spectral microtomography information on the density and the energy dependence of the linear attenuation coefficient for medical research related to obesity.
- Investigation of the possibility of isolating radiopaque substances in the body according to the energy dependence of the linear attenuation coefficient in order to study drug delivery using radiopaque markers.
- Studies of the principle possibility of creating equipment based on Medipix detectors, suitable for use in clinical practice (assessment of parameters such as the scan time and the amount of absorbed dose depending on the image quality).
- Studies of the possibility of creating microdosimetric probes based on Timepix detectors for measurements of the equivalent dose.
- The study of ores and mineral raw materials will continue, the potential usage of spectral microtomography to identify the mineral phases will be studied.

Project authors

Project leaders

- Project leader: G. Shelkov
- Deputy project leader: A. Zhemchugov

DLNP (18 people):

S. Abu Al Azm, M. Demichev, D. Dedovich, A. Gongadze, M. Gostkin, A. Guskov, S. Kotov, D. Kozhevnikov, V. Kruchonok, N. Kuznetsov, A. Lapkin, A. Leyva Fabelo, A. Nozdrin, V. Pavlov, I. Potrap, S. Porokhovoy, P. Smolyanksiy, V. Tokareva

VBLHEP (6 people):

A. Averyanov, A. Korotkova, D. Krivenkov, J. Lukstins, A. Maximchuk, S. Starikova

FLNR (1 person):

S. Mitrofanov

Cost estimates for the Project (kUSD)

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
	detector assembly site	33	0	2	31
	readout electronics 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

Scientific cooperation

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, Tomsk
- St. Petersburg State University, St. Petersburg
- Mechnikov Northwestern State Medical University, St. Petersburg
- Federal State Institution of Health Sokolov Clinical Hospital № 122, St. Petersburg
- Moscow State University, Moscow
- International University of Nature, Society and Man, Dubna
- Petrovsky Russian Research Center of Surgery of the Russian Academy of Medical Sciences, Moscow

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

Summary and conclusions

- The Project "Novel semiconductor detectors for fundamental and applied research" accomplished all of its planned goals in 2015-2017 (with a few exceptions).
- The existance of this JINR Project allowed to attract extrabudgetary subsidies from the Russian Ministry of Education and Science within the framework of the joint Russian-German project GALAPAD-2.
- Due to this Project (in part) JINR became a full member of the Medipix collaboration.
- Many areas of investigations, both new and old, require further research and development.

We ask the Committee to support our proposal and to approve prolongation of the Project for the period of 2018-2020.