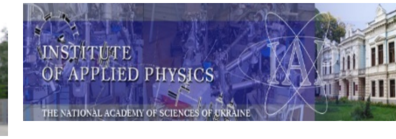




Development of versatile test platforms for research of radiation detectors for medical applications - *first steps of Ukrainian partners of LIA IDEATE*

STCU project

Speaker: Oleg Bezshyyko (TSNUK)

Orsay 2017

The fifth French-Ukrainian workshop on the instrumentation developments for HEP, November 6-8, 2017, LAL, Orsay

R&D and educational experimental platforms for instrumentation for medical imaging and other applications

in the framework of

France-Ukraine International Associated Laboratory (LIA)

"**I**nstrumentation **D**evelopments for **E**xperiments at **A**ccelerator facilities and accelerating **TE**chniques" – **LIA IDEATE**

Proposal by the LIA Ukrainian teams

(56 participants)

to

STCU ***(SCIENCE & TECHNOLOGY CENTER IN UKRAINE)***

Ukrainian teams (Participating Institutions):

*Taras Shevchenko National University of Kyiv of Ministry of Education and Science of Ukraine (**TSNUK**)*

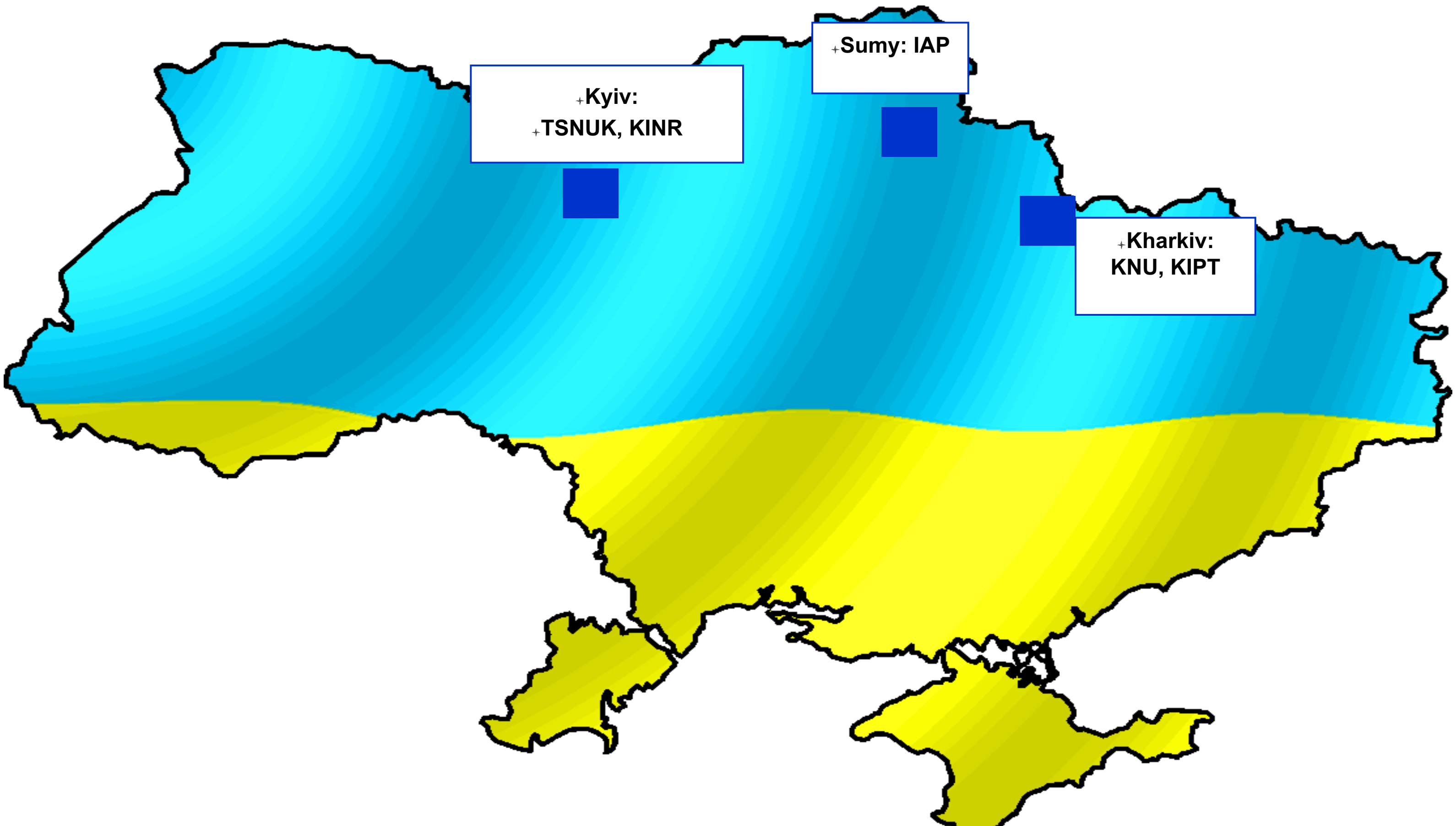
*V. N. Karazin Kharkiv National University of Ministry of Education and Science of Ukraine (**KhNU**)*

*National Science Center "Kharkiv Institute of Physics and Technology" of National Academy of Sciences of Ukraine (**KIPT**)*

*Kyiv Institute for Nuclear Research NASU of National Academy of Sciences of Ukraine (**KINR**)*

*Institute of Applied Physics NASU of National Academy of Sciences of Ukraine (**IAP**)*

Ukrainian teams propose:



the development of comprehensive set of experimental techniques and versatile test platforms for development, characterization and testing of wide range of radiation detector systems for medical imaging, beam and dose monitoring and other medicine applications. On the base of these platforms set of prototype systems for using in radiation therapy and diagnostics will be designed and built. The set of versatile test platforms is divided territorially **on Kyiv platform** and **Kharkiv platform**.

Construction/operation of the platforms will be assisted by the CNRS (LAL) scientists and engineers (advisory and technical expertise) via the LIA program

Sites to host the platforms

- **Two sites** at major universities of Ukraine : Taras Shevchenko National University of Kyiv and V. N. Karazin Kharkiv National University

The **hosting universities will engage** :

- ❑to provide the location;
- ❑to cover electricity/water/… consumption;
- ❑to provide technical support of their platform with the local manpower;
- ❑to provide access to the platform site and equipment, to provide required help and assistance to the LIA partners;
- ❑to receive partner's trainees.

Each site provides a **free of charge assistance (except for cost of materials)** to the **entire group of LIA partners**

Kyiv platform

Platform profile:

generic services

- *MPGD, SiPM, scintillating detectors*
- *Detector-equipped phantoms*
- *Open source dose planning system for radiation oncology*
- *X-ray "phase contrast" imaging techniques*

Kharkiv platform

Platform profile:

*R&D of **planar detectors** (resistive detectors, Si PIN detectors and photosensors, SiPM, MAPS etc.) and **detector systems** (single detectors and arrays of Si PIN photosensor + scintillator, Si PIN detector + metallic Gd converter) operated at room temperature*

Kyiv platform : instrumentation

Generic tools, services

- Cutting laser machine (micromachining)
- Multi-axis (5 or more) machining center
- Wire bonding machine
- Hot air infrared soldering station

Tools for specisic developments

- Platform for major R&D of MPGD detectors
- Platform for major R&D of silicon photodetectors in Geiger mode - SiPM
- Irradiation by isotope sources: γ, β, α, neutrons, D-D neutron generator

- Provided entirely by hosting University

- Part of materials and equipment requested from STCU, main development by the LIA team

- Equipment requested from STCU

Kharkiv platform : Instrumentation

Generic tools, services

- Different Meters (RLC, V/I)
- Universal oven
- Microposition probes
- Stereo Microscope with Camera
- Motorized Stages
- Power Supplies
- Labware for electrical measurements
- Light-tight chamber
- Ultrasonic microwelding machines
- Ingot cutting installations
- Precision balance

Tools for specific developments

- Precision microwire bonding facilities
- Automated facilities of detector testing
- Spectrometric read-out system
- Spectrometric measurement channels
- Sputtering and annealing installations
- Universal vacuum station for ion plasma processing
- Probe and microprobe stations
- Sets of standard radiation sources

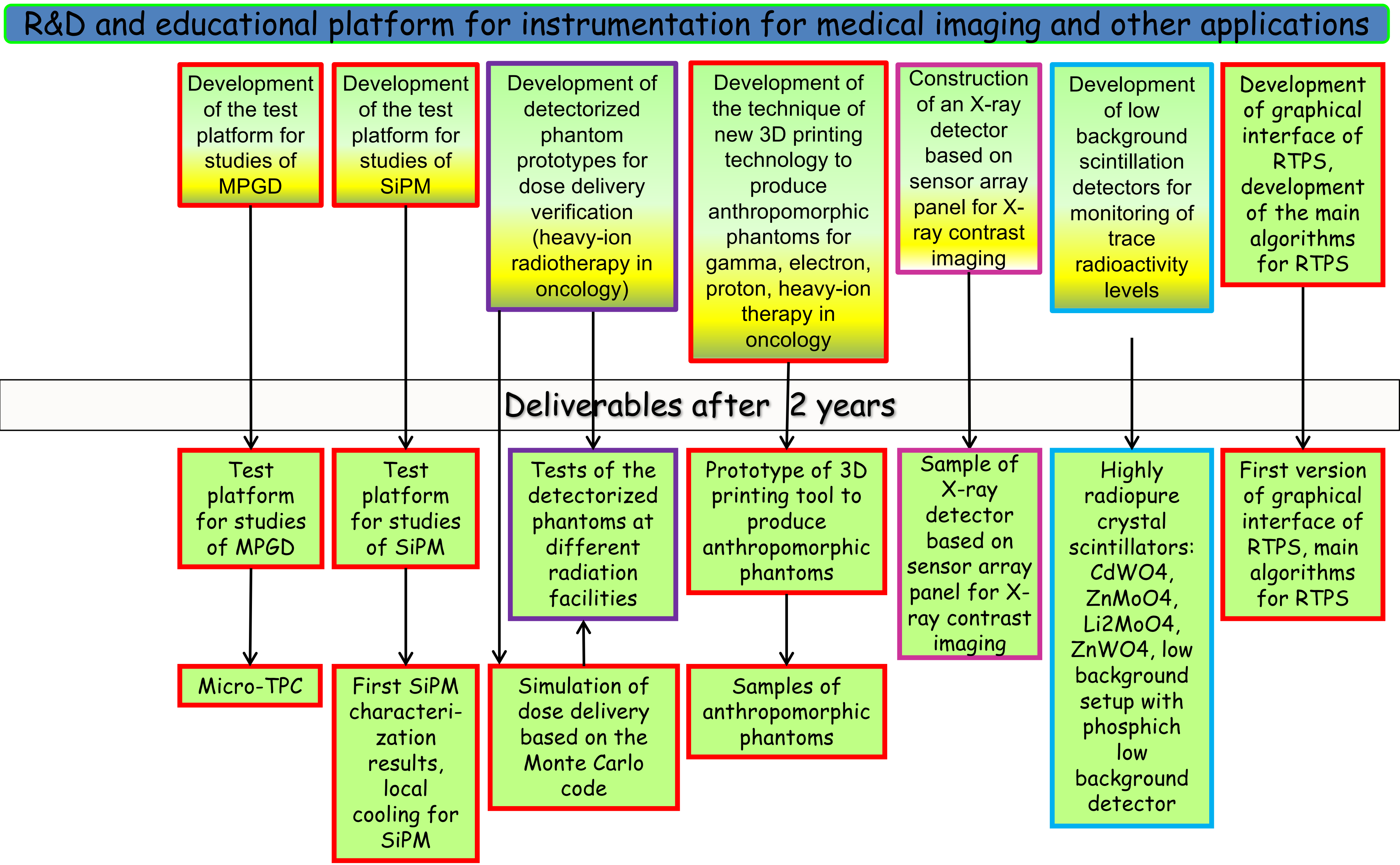
- Provided entirely by hosting University

- Part of materials and equipment requested from STCU, main development by the project team

- Equipment requested from STCU, the project team ensures installation/commissioning/operation/support

Construction of the Kyiv platform: responsibilities

Responsibilities: TSNUK KINR-LP KINR-HEP IAP



Kharkiv platform : Instrumentation

Generic tools, services

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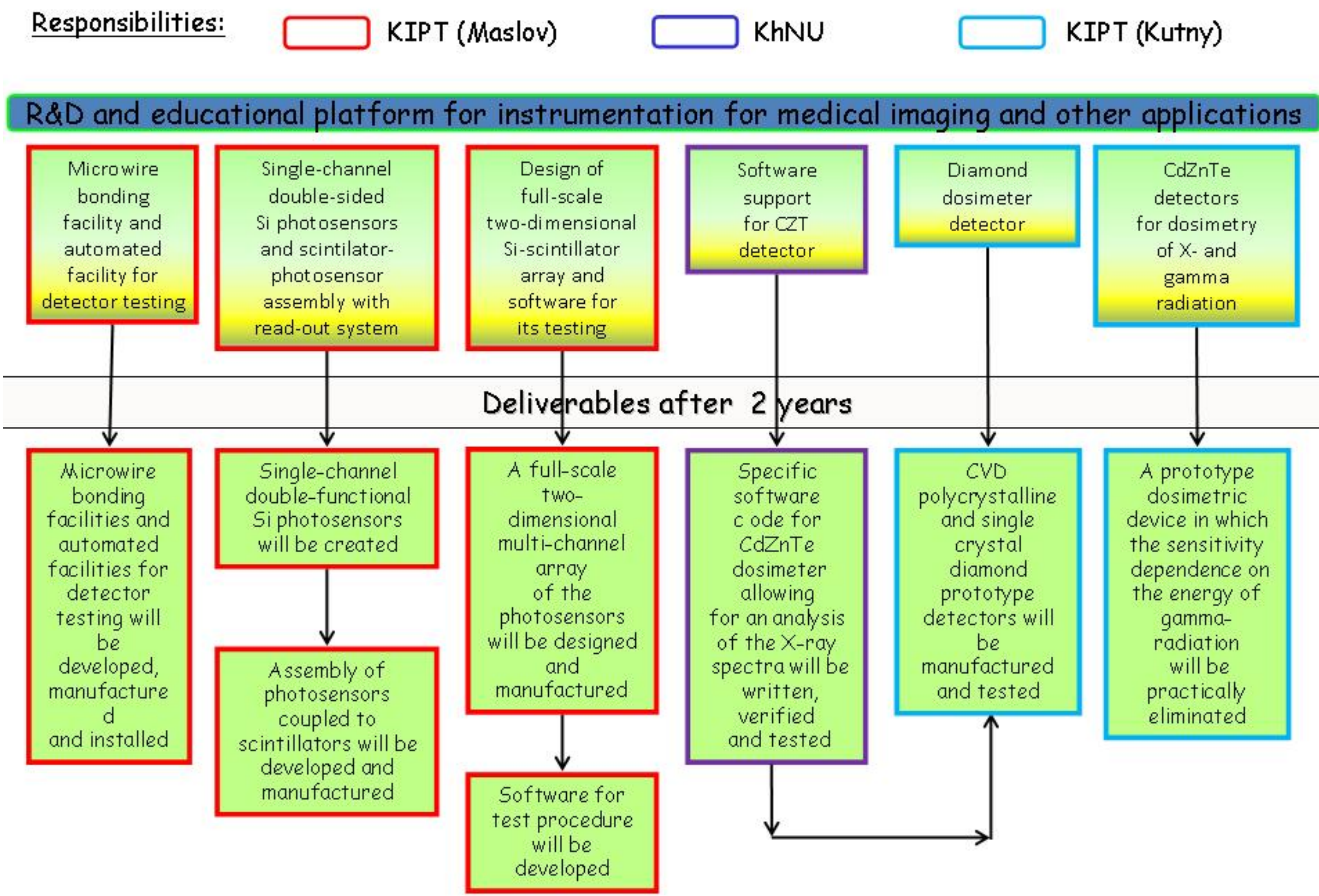
Construction of the Kharkiv platform: responsibilities



Kyiv platform

F.Danevich group of KINR

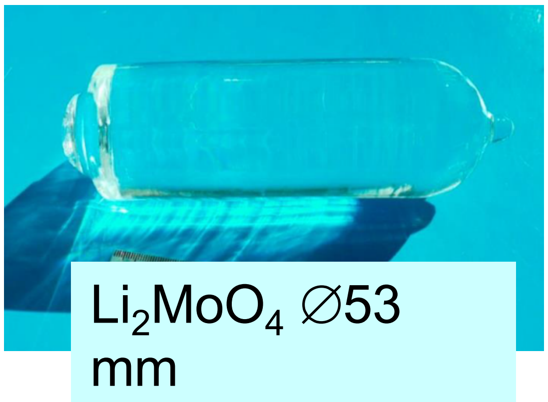
Responsibility – Fedor Danevich

Low background scintillation spectrometer to measure low level radioactivity in crystal scintillators and in samples of materials will be developed in the framework of the project. High performance radiopure $CdWO_4$, $ZnMoO_4$, $Li2MoO_4$, $ZnWO_4$ crystal scintillators will be developed and tested. New nuclear data (more accurate half-life values or new improved half-life limits) on radioactivity of cadmium, tungsten, zinc and molybdenum isotopes will be obtained.

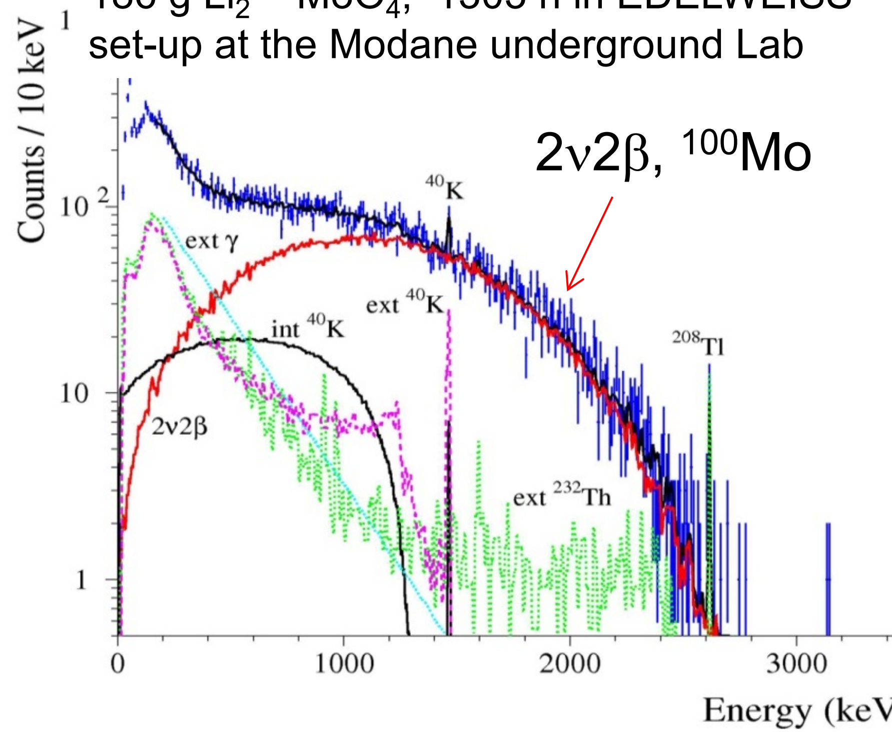
Development of low background scintillation detectors

R&D of $ZnMoO_4$ and Li_2MoO_4 cryogenic scintillation detectors

Collaboration with CSNSM, Orsay, France



Production of high quality zinc ($ZnMoO_4$) and lithium molybdate (Li_2MoO_4) crystal scintillators (including scintillators from enriched ^{100}Mo) has been developed



High performance $Li_2{}^{100}MoO_4$ scintillating bolometers:

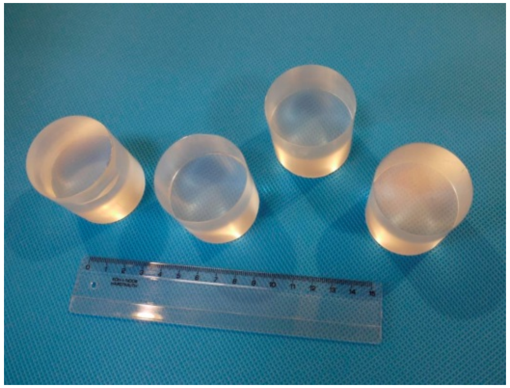
- Energy resolution FWHM = 4-6 keV at 2615 keV
- Particle discrimination capability: $DP_{\alpha/\beta} = 9 - 18$
- Low radioactive contamination: < 10 μBq/kg of ^{226}Ra and ^{228}Th

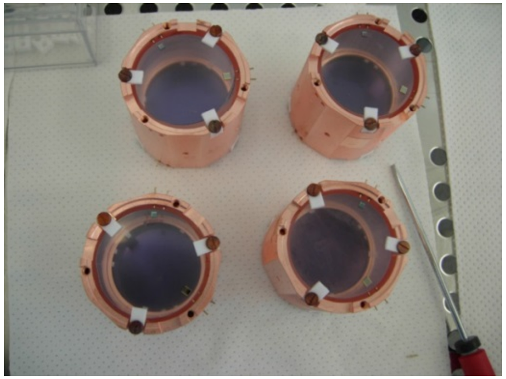
$$T_{1/2} = [6.90 \pm 0.15(\mathrm{stat}) \pm 0.37(\mathrm{syst})] \times 10^{18}\ \mathrm{yr}\ [1]$$

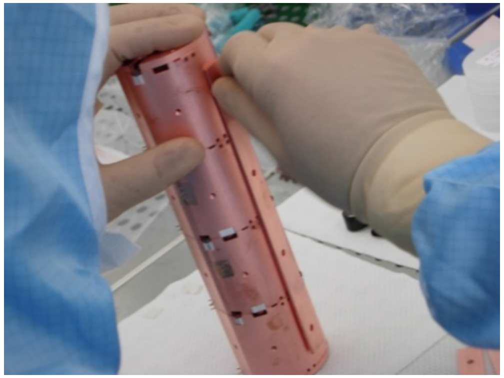
An important physical result: the most accurate $T_{1/2}$ of ^{100}Mo

[1] E. Armengaud et al., Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search submitted to EPJA ; arXiv:1704.01758v2 [physics.ins-det] 4 Oct 2017

A pilot $0\nu2\beta$ experiment with 20 radiopure $Li_2{}^{100}MoO_4$ crystal scintillators should start in the beginning of 2018







- 20 enriched $Li_2{}^{100}MoO_4$ crystals are produced
- Assembling of the $Li_2{}^{100}MoO_4$ detectors is in progress aiming to start a pilot experiment beginning of 2018

Assumed background is 10^{-3} counts/yr/kg/keV in 10 keV window centered at $Q_{2\beta}$ of ^{100}Mo:

Sensitivity to $0\nu2\beta$ decay of ^{100}Mo over 6 month:

$$\lim T_{1/2}^{0\nu} \sim 1.3\times10^{24}\ \mathrm{yr} \quad \Rightarrow \quad \langle m_\nu \rangle \approx 0.33\ \mathrm{eV} - 0.56\ \mathrm{eV}$$

- Production of the next 20 $Li_2{}^{100}MoO_4$ detectors is foreseen in 2018

Sensitivity with 40 detectors over 3 yr:

$$\lim T_{1/2}^{0\nu} \sim 1.5\times10^{25}\ \mathrm{yr} \quad \Rightarrow \quad \langle m_\nu \rangle \approx 0.1\ \mathrm{eV} - 0.17\ \mathrm{eV}$$

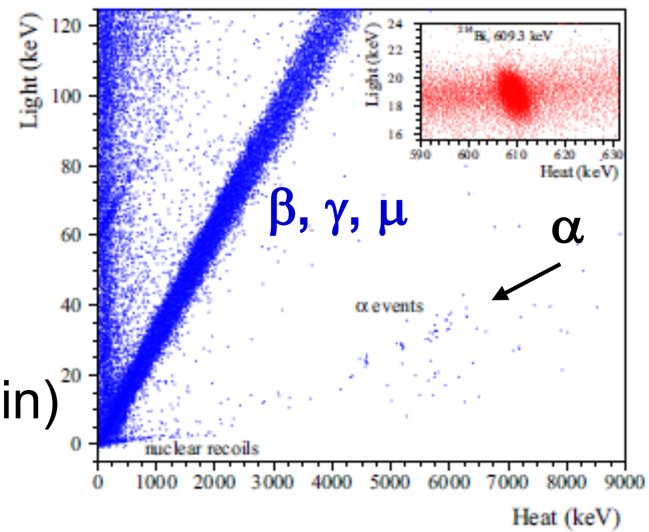
Cryogenic search for 0ν2β decay of ^{116}Cd is in preparation

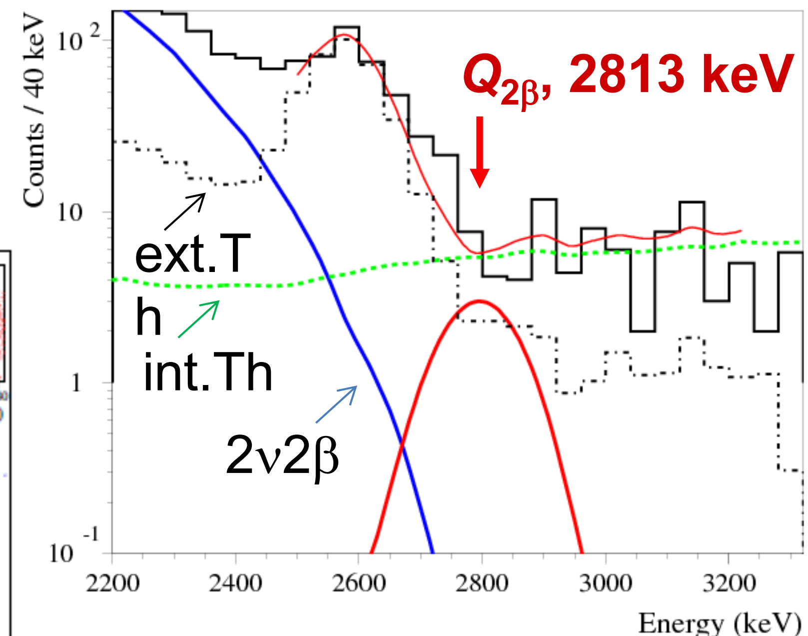
project **CYGNUS**: Cryogenic search for neutrinoless double beta decay of cadmium

- Energy resolution: 130 keV → 5-7 keV at $Q_{2\beta}$ [1,2]
- Background can be reduced: → 1.4 cnts in 10keV ROI over 3 yr

The reduction of background (mainly ^{208}Tl) is expected due to particle discrimination and high energy resolution to αs

$^{212}Bi \xrightarrow{\alpha} {}^{208}Tl \xrightarrow{\beta} (T_{1/2} \approx 3\ \text{min})$





Search for 0ν2β decay of ^{116}Cd with advanced sensitivity: $\lim T_{1/2}^{0\nu} \sim 8\times 10^{23}$ yr

Demonstration of ^{116}Cd option capability for the large scale experiment (i.e., CUPID)

[1] A.S. Barabash et al., EPJC 76 (2016) 487
[2] C. Arnaboldi et al., Astropart. Phys. 34 (2010) 143.

Kyiv platform

V.Pugach group of KINR

<u>Responsibility – Valery Pugatch</u>

Within the framework of the project the new experimental setup for the studies in the field of the spatially fractionated hadron therapy will be designed, built and tested. It will include tissue equavalent phantom equipped with ultrathin metal microdetectors and readout electronics, multi-slit and matrix collimators for shaping 1D and 2D hadron multi-beam structures.

Features of those setup components will be defined from the Monte Carlo simulations aimed at optimization of the irradiation field structure on the basis of the Peak-toValley-Dose-Ratios for different types of hadron beams and their energies determined by the depth of a tumor location and its shape.

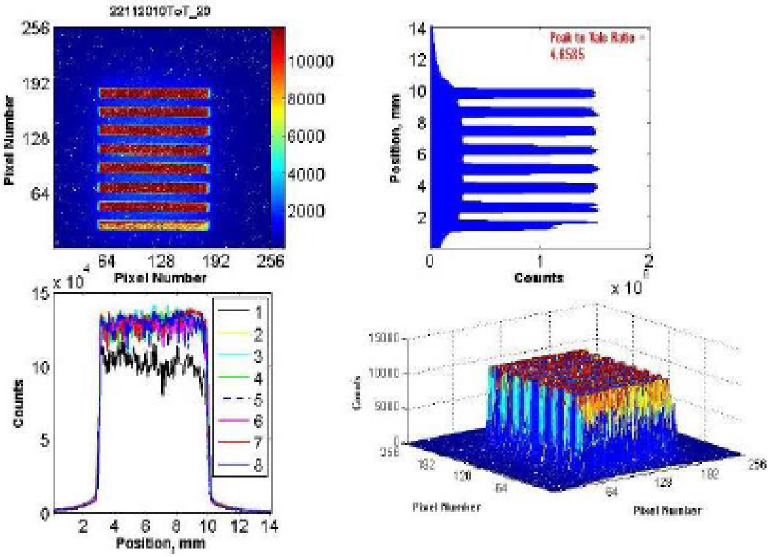
Radiation hard metal micro-strip sensors will be produced and instrumented by the readout microelectronics. Tests of the Detectorized Phantom will be performed at the KINR isochronous cyclotron U-240.

Shaping and monitoring of mini-beams of charged particles and gamma-rays for spatially fractionated radiation therapy

Make Irradiation field inhomogeneous:

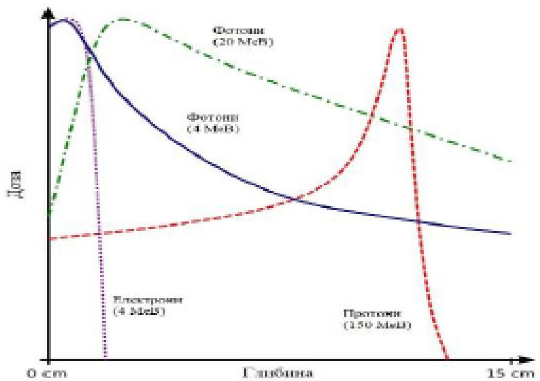
- Shape it as mini-beams (0.6 mm width and 1.2 mm periodical structure) or micro-beams (50 µm and 100 µm periodical structure)
- Developed for the synchrotron radiation at ESRF (Grenoble)
- Tested at animals – positive effect due to the increased dose in the open area of the collimator.
- Criteria of profit – **PVDR**
- Measured for the first time in real time in 2011 in Collaboration KINR_ESRF_Medipix(CERN) – spatial dose distribution in agreement with gafchromic films (off-line, time consuming procedure, yet with a perfect position accuracy – few micrometers).

[V. Pugatch et al. Nucl. Instr. and Meth. A682 (2012) 8-11]

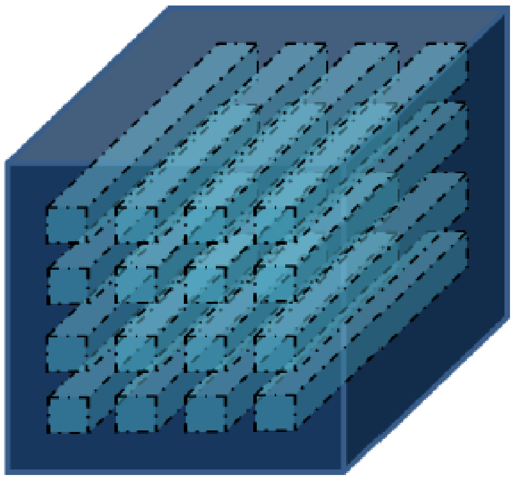


New idea (IMNC, Yolanda Prezado) – to implement it for the hadron beams (feasibility studies started at HIT – Heidelberg in 2014 (KINR-IMNC-CERN)

[V. Pugatch, et al. Characterization of equipment for shaping and imaging hadron minibeams. NIM A872 (2017) 119-125.]



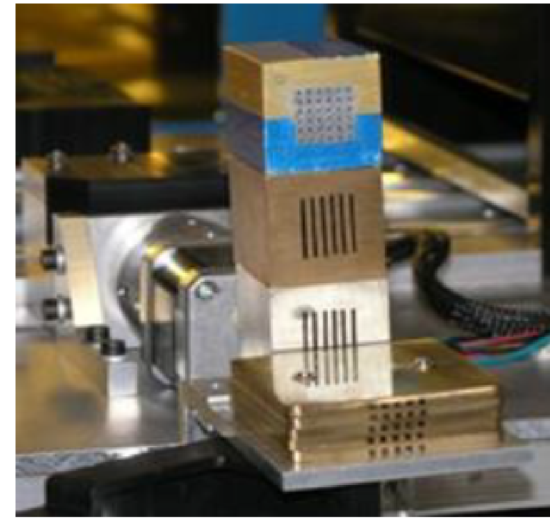
Equipment for shaping



Matrix collimators
(holes of 1.5 x1.5 mm^2 and c-t-c distance of 4 mm)

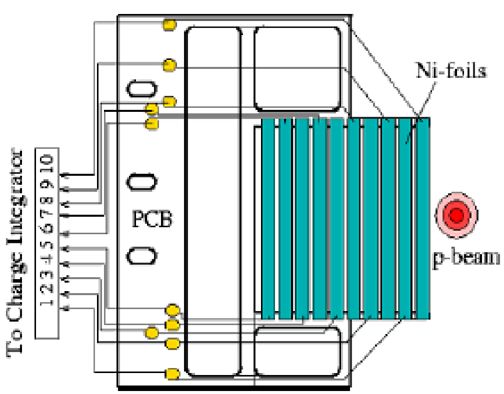
Slit Collimators
(1.0 mm width, 2.5 mm c-t-c distance)

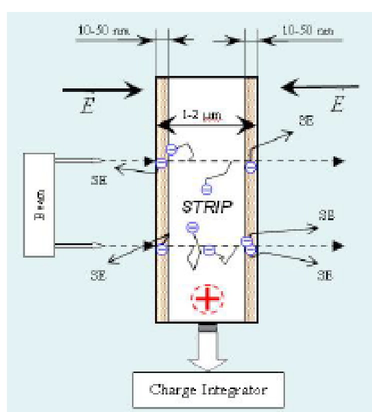
Material: aluminum, brass, lead



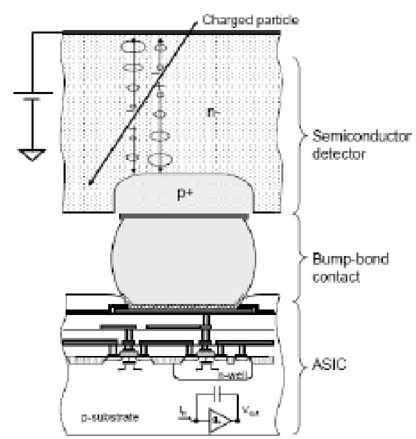
Metal Microdetectors are applied For imaging (Technology at KINR- patented).

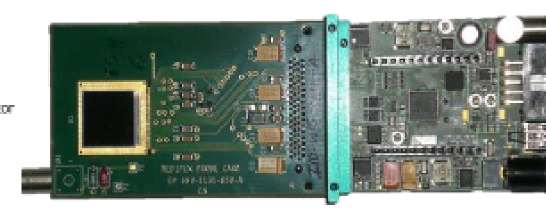
TimePix





High Radiation tolerance (more than 100 MGy)
Nearly transparent sensor – 1 µm thickness





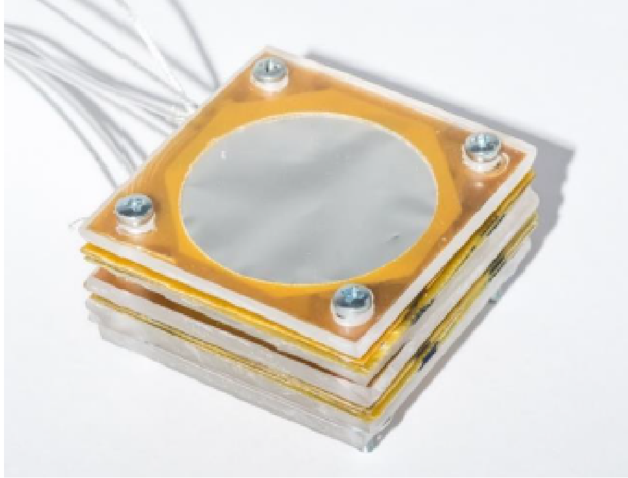
Hybrid pixel detector with the n-Silicon sensor chip and the TimePix electronics chip connected via bump bonds.

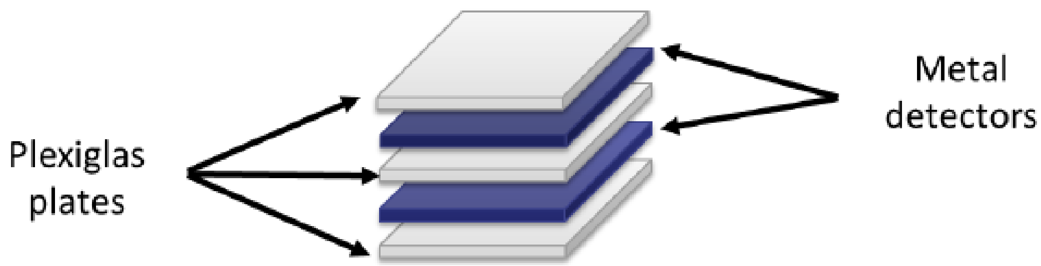
Detectorized Phantom

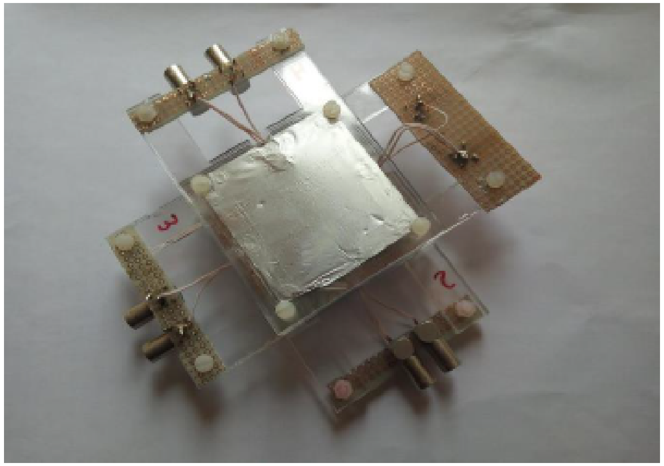
Development of detectorized phantom prototypes for dose delivery verification (heavy-ion radiotherapy in oncology).

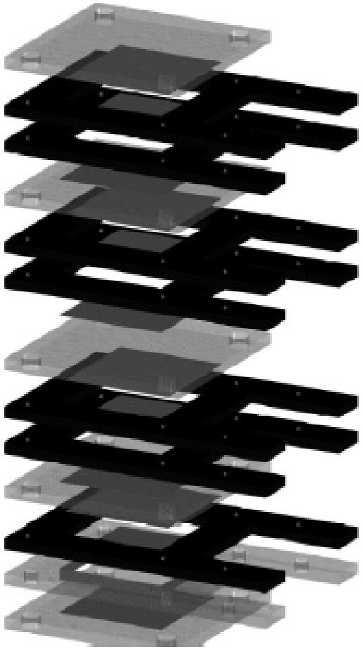
Few prototypes have been produced and tested.

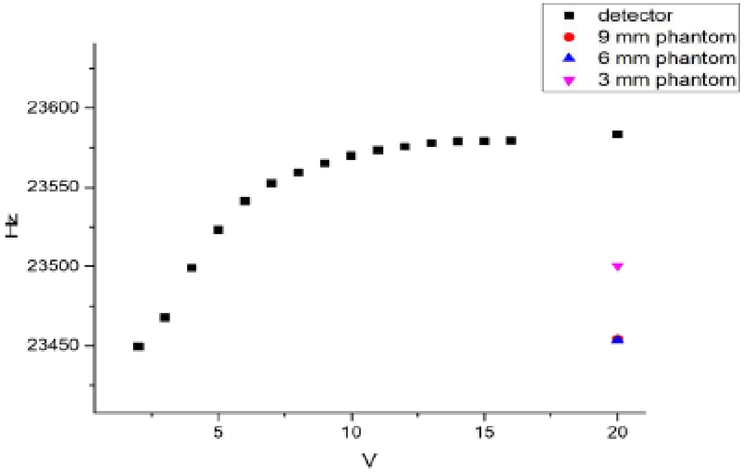
Feasiblity of the approach has been demonstrated.











Kyiv Institut for Nuclear Research

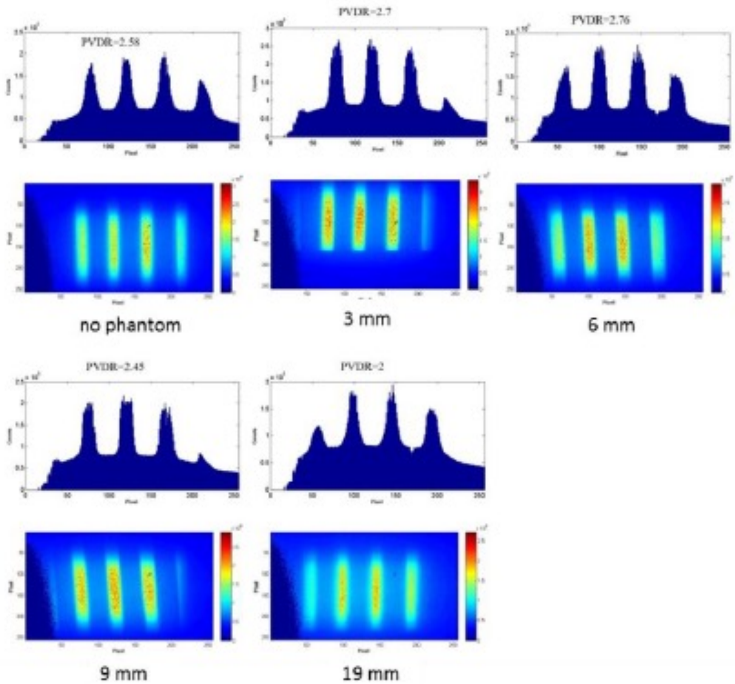
Testing of the equipment at the Clinac system

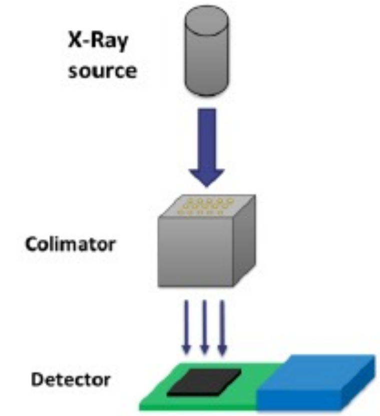
Beam Energy: 6-12 MeV

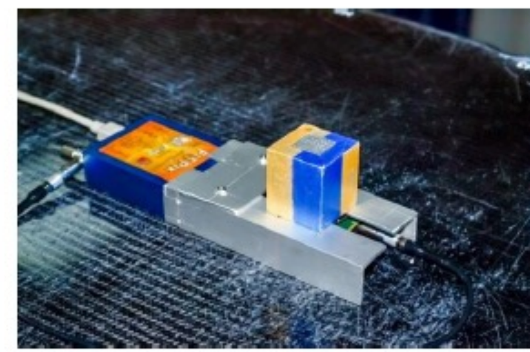
Pulse Width: 5 µs

Pulse Repetition Rate: 20-100 Hz

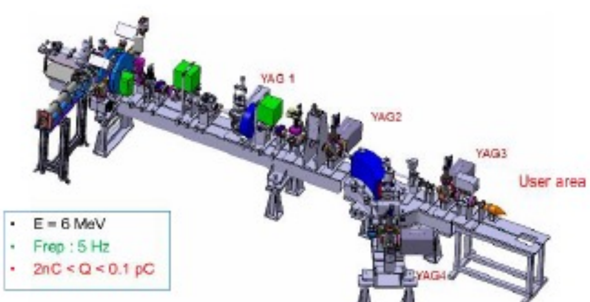
Beam type: Photon, electron

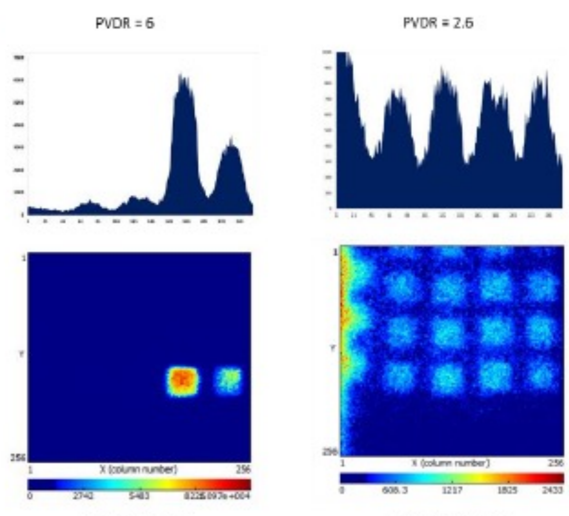






Testing of the equipment at the PHIL (LAL).





Kyiv platform

TSNUK (Kyiv University)

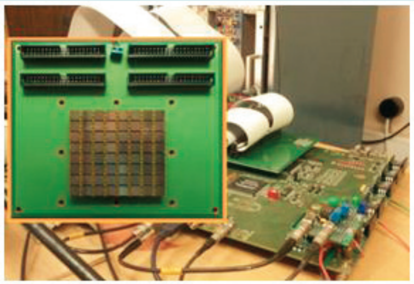
Responsibility – Oleg Bezshyyko

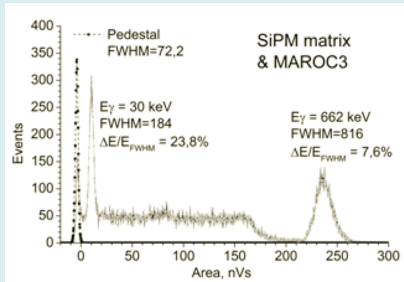
- Developed and built test subplatform for studies of MPGD detectors with automated systems of gas control and power supply (low and high voltage), data acquisition system, mechanical sub-system.
- Developed and built micro-TPC system on the base Micromegas/Ingrid chip using subplatform for studies of MPGD detectors.
- Developed and built test subplatform for studies of silicon photodetectors using Geiger mode – SiPM with automated systems of 3D movement (better than 5 μ), control of temperature conditions (-70^0C - $+50^0$C), precise power supply and measurement of current of SiPM, laser (light) system (picosecond lasers and wide range of wavelength of light source), data acquisition system, mechanical sub-system.
- A small prototype for 3D printing system to print complex structures of anthropomorphic phantoms with using of various dose detector systems.
- Phantom samples.
- Open source RTPS (Radiation Therapy Planning Systems).

Possible applications of SiPM in medicine

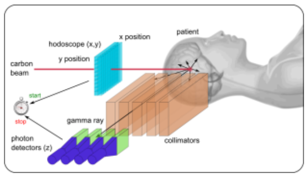
Development of SiPM-based gamma camera, full-body SPECT

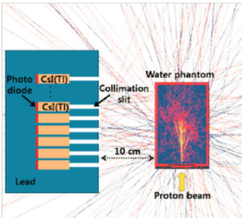
(2015)
(2015)
(2011)





Prompt gamma camera for real-time range control in Proton Therapy; dose distribution in real time for ion beam therapy by means of prompt gamma detection; prompt gamma imaging with a slit camera





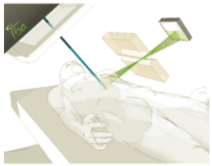
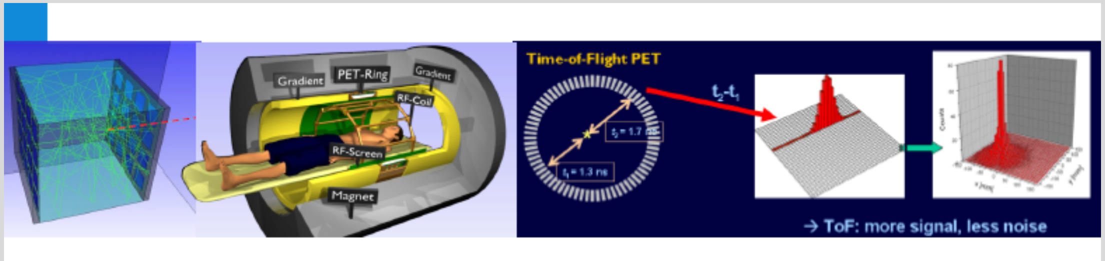


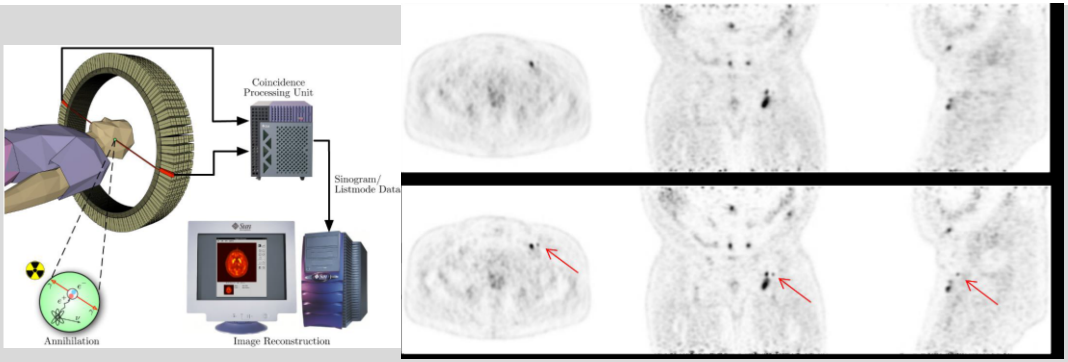
Table 5.2 Comparison of the most common photo-detectors for scintillation counting.

Property	PMT	PIN	APD	SiPM
Q.E. or PDE	0.25	0.8	0.8	0.5
Gain	10^6	1	10^2	10^6
Operational bias	1000 – 2000 V	10 V	100 – 200 V	$< 100V$
Mechanical robustness	Low	High	Medium	High
Readout electronics	Simple	Complex	Complex	Simple
Form factor	Bulky	Compact	Compact	Compact
Rise time	Fast	Medium	Slow	Fast
Sensitivity to magnetic fields	Yes	No	No	No

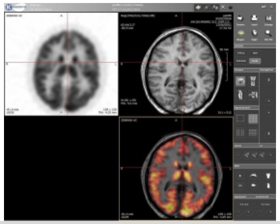
Ultra precise timing with SiPM-Based TOF PET scintillation and Cherenkov detectors

(2015)
(2009)

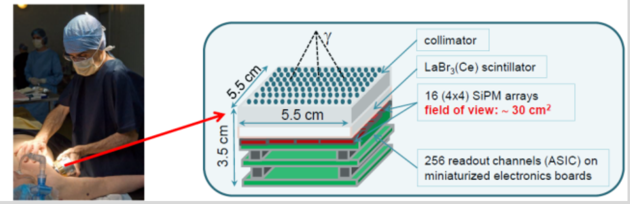




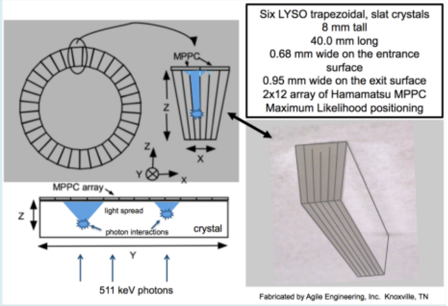
PET/MR System With Time-of-Flight Capability



SIPMED camera

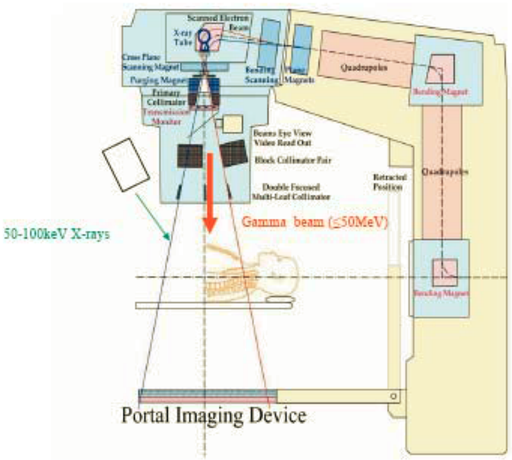


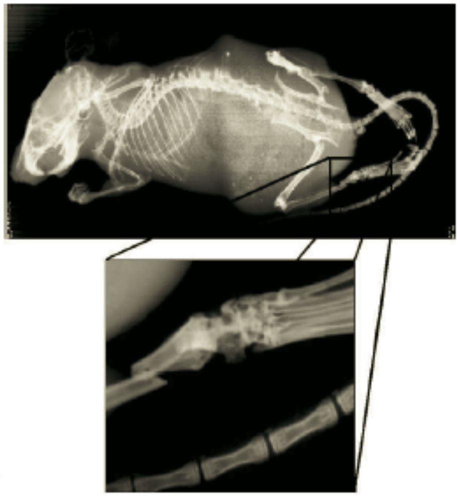
Depth Of Interaction (DOI) determination



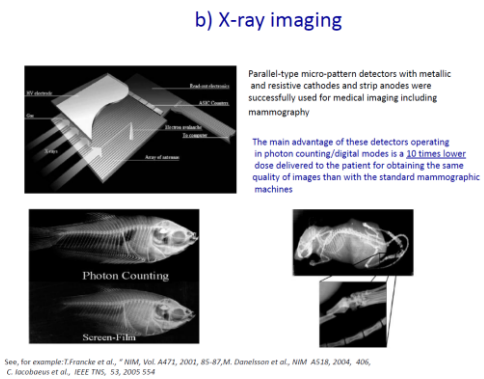
Possible applications of MPGD in medicine

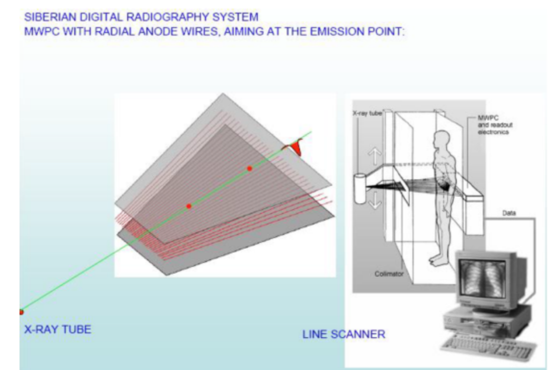
- Portal Imaging





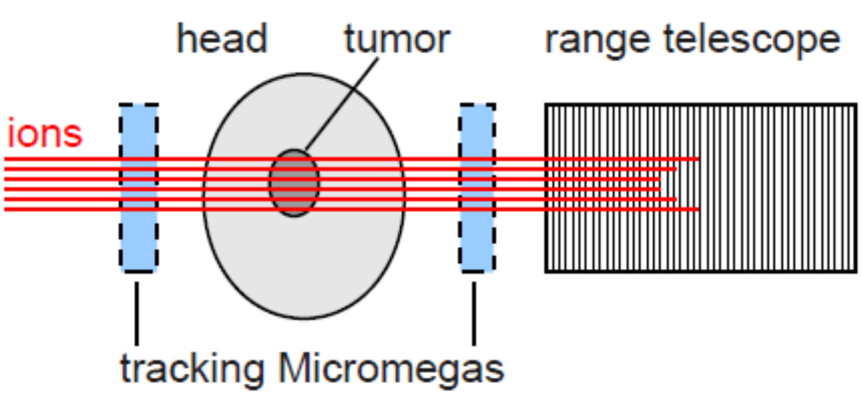
- Simple X-ray imaging system and system for a medical application as a proton beam monitor





Originally developed by Novosibirsk group, a modified version based on micropattern detectors was developed by Charpak company Biospace

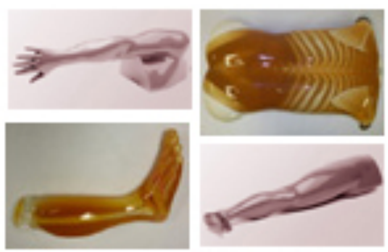
- Application of Micromegas in medical ion transmission tomography

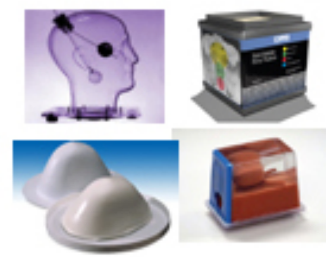


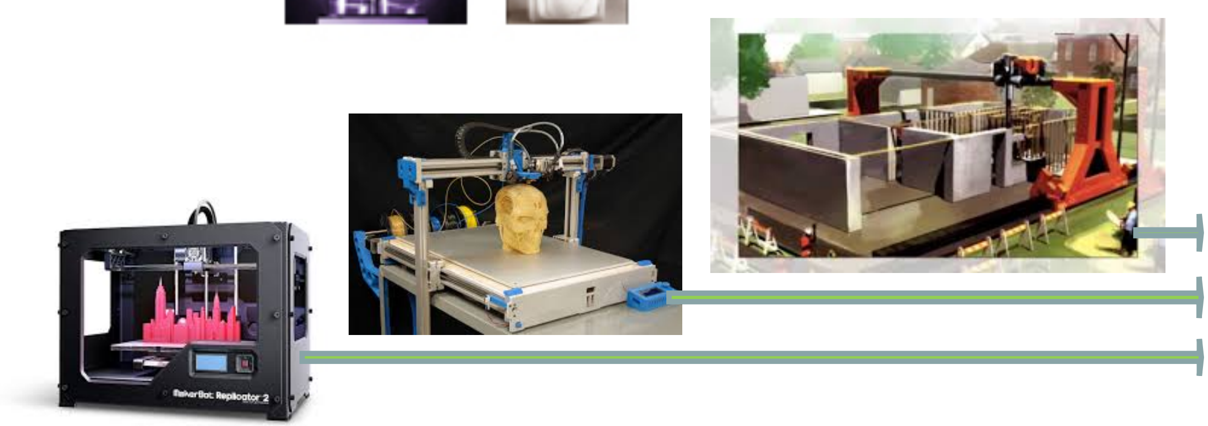
- Fast and thermal neutron detection

- **Possible collaboration with RD51 (CERN) for further developments**

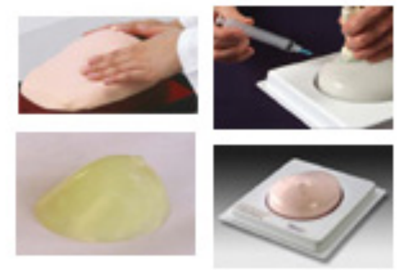
Anthropomorphic phantoms





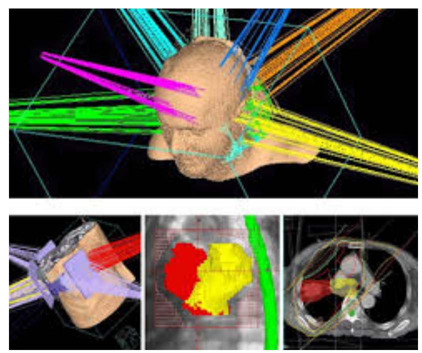


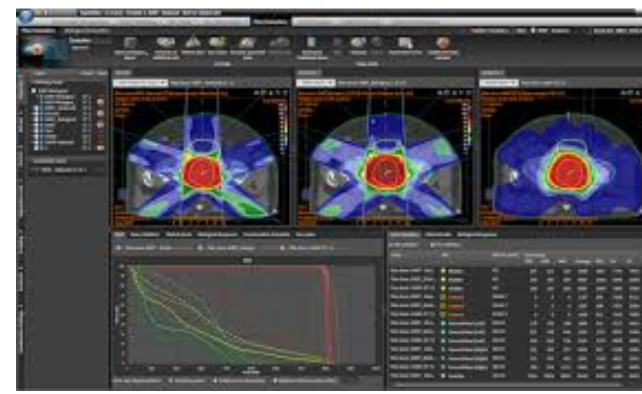
Radiation Therapy Phantoms



3D printer for Phantoms

Planning systems for dose calculations for radiation oncology - RTPSs





Commercial RTPSs (Pinnacle, XiO, Eclipse,TMS, KonRad, iPlan etc.) – are very power systems but also very expensive and tied strongly to a specific manufacturer equipment. It restricts firmly possibilities for effective education of new personal, students in universities (medical physics, clinical dosimetry specialties…), providing of second calculation path to estimate the dose obtained by patient (requirements of regulation documents).

Open Source functional RTPS – solution of this problem

Calculation algorithms and methods - *Monte Carlo method (fast variants),* Semi-Empirical algorithms (also called Correction or Factor based) -> model based algorithms, Pencil Beam algorithm (Convolution), Convolution-Superposition algorithms…

Development of **open source** planning system for dose calculations for radiation oncology - RTPS

Comparison of chosen approaches and algorithms with reputable commercial RTPS of vendors well-known in the world

Development of the main semi-analytical algorithms for RTPS

Creation of first variant of graphical interface of RTPS

Development of the main Monte Carlo algorithms for RTPS

Using GPU, other parallel hardware tools: estimations

Testing of RTPS

Kyiv platform

IAP (Sumy)

Responsibility – Dmitry Nagorny

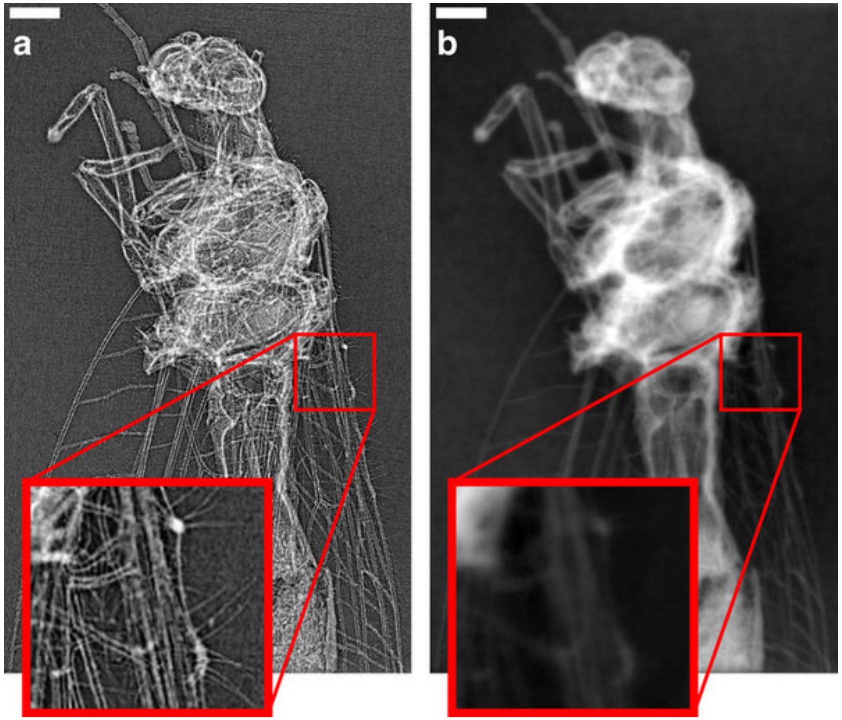
- In the framework of the project a prototype of the detector based on multisensor array will be designed, manufactured and tested. The detector will be focused on the research on study of X-ray phase contrast. Testing of the detector will be carried out at the channel quasi-monochromatic X-ray end-station at the IAP NAS of Ukraine.

Technology of X-ray phase contrast imaging (PCI)

http://www.nature.com/articles/srep13581 (2015)
http://www.ncbi.nlm.nih.gov/pubmed/23220766 (2013)
http://www.ncbi.nlm.nih.gov/pubmed/22330515 (2013)
https://en.wikipedia.org/wiki/Phase-contrast_X-ray_imaging

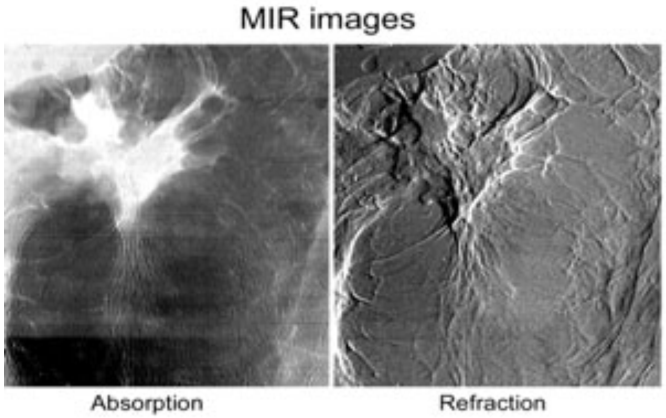
Quantitative X-ray phase-contrast microtomography from a compact laser-driven betatron source

http://www.nature.com/ncomms/2015/150720/ncomms8568/full/ncomms8568.html



(**a**) The image shows a selected single-shot radiograph dominated by X-ray in-line phase contrast. Small details are highlighted due to the strong edge enhancement effect (see insets of magnified sections). (**b**) The corresponding quantitative phase map was retrieved using a single-material constraint.

http://mirc.iit.edu/research/phase-contrast-x-ray-imaging/



Phase-contrast X-ray imaging

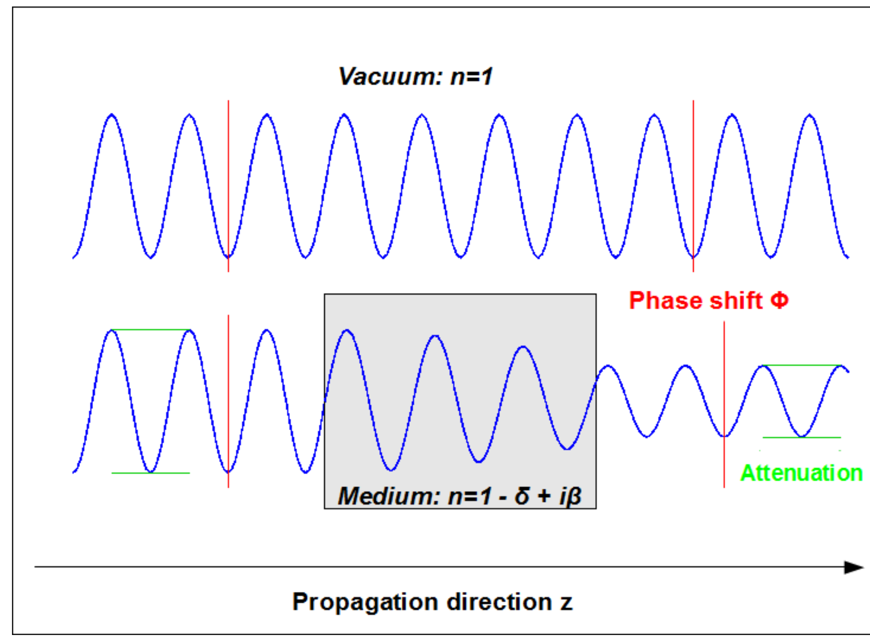
Phase-contrast X-ray imaging (PCI) is a general term for different technical methods that use information concerning changes in the phase of an X-ray beam that passes through an object in order to create its images.

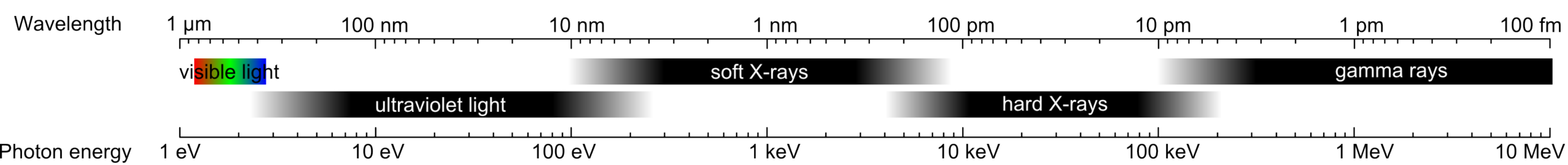
$$\Psi(z) = E_0 e^{inkz} = E_0 e^{i(1-\delta)kz} e^{-\beta kz}$$

the phase shift

an exponential decay factor
decreasing the amplitude of the wave

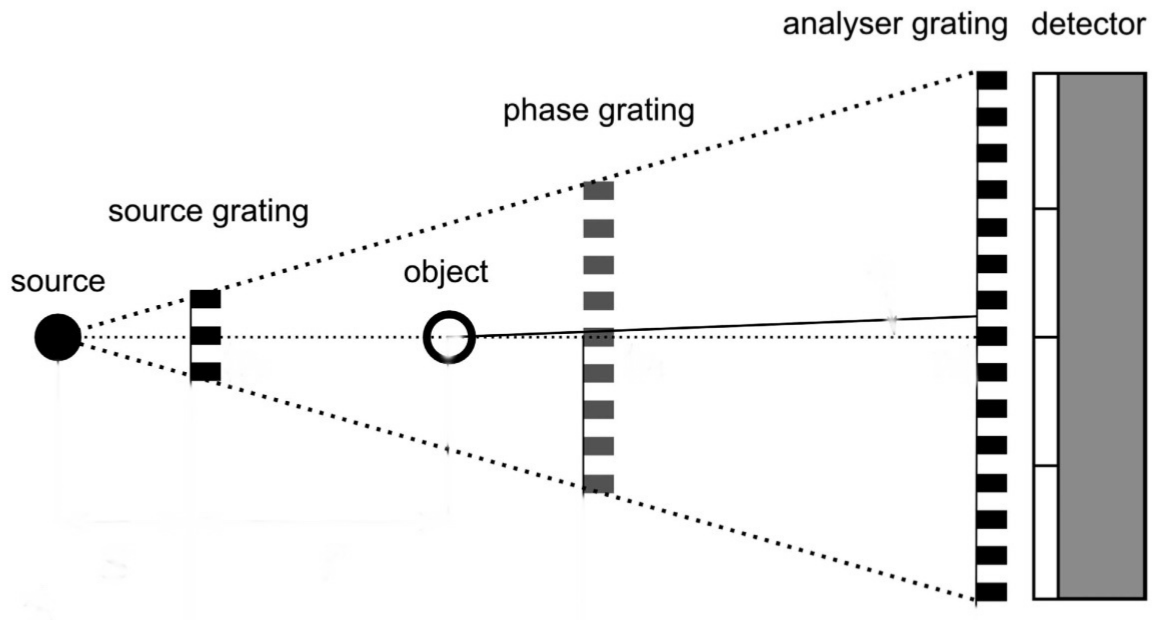
$\delta \propto k^{-2}$ $\beta \propto k^{-4}$





Phase-contrast X-ray imaging.
Experimental realisation

- Crystal interferometry
- Grating Bonse-Hart
- Analyzer-based imaging
- Propagation-based imaging
- Edge-illumination
- Grating-based imaging (Talbot interferometry)

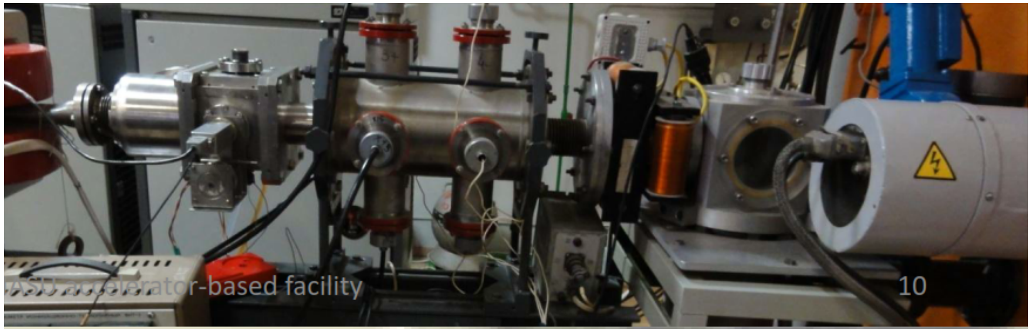


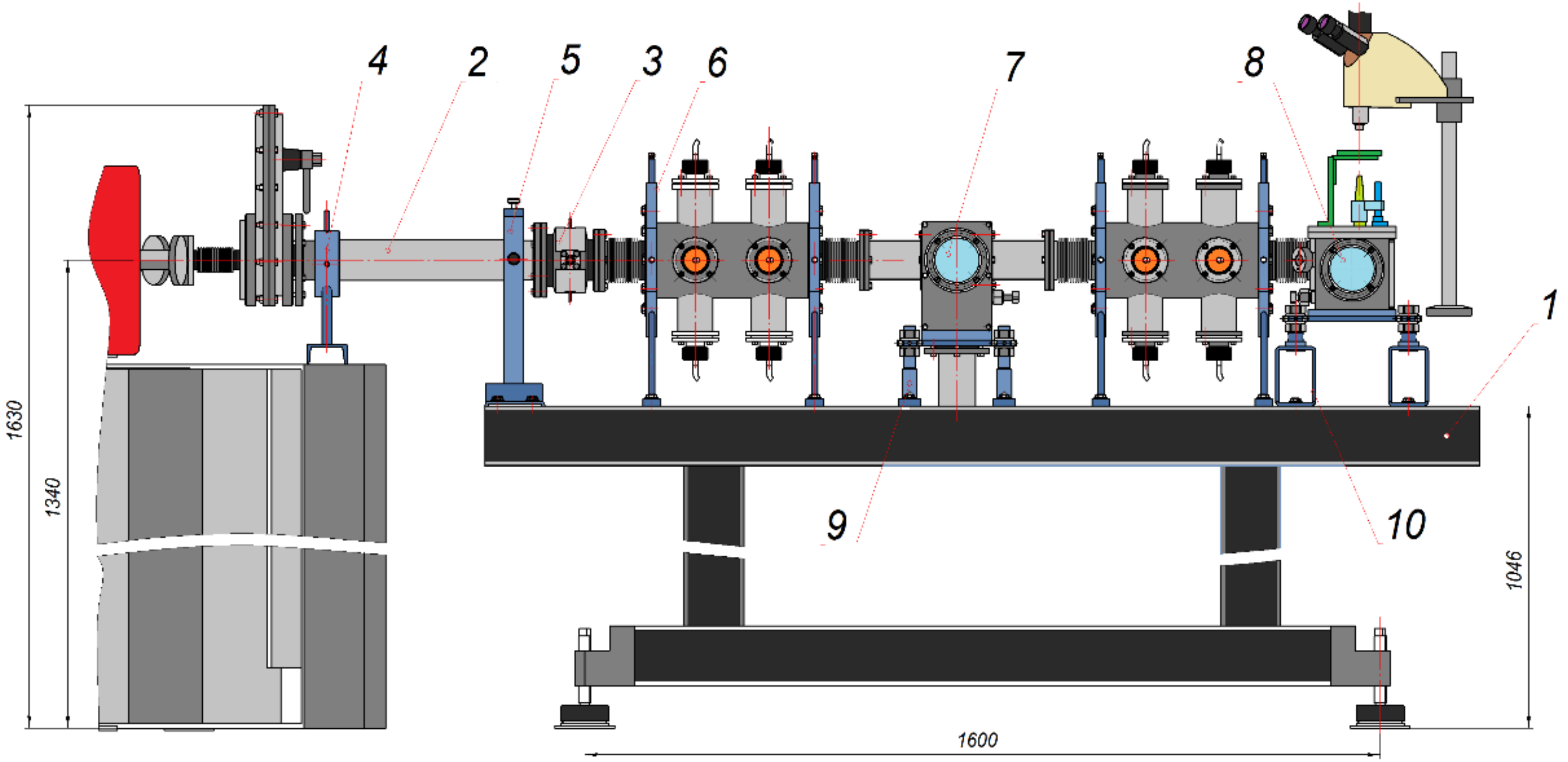
Required characteristic of radiation for X-ray phase contrast

Energy range	ΔE/E	Source size	Size on the object	Flux on the object	Coherence
> 10 keV	3%	small	50 cm	> 10^(9) ph/s	yes

Accelerators based compact source of quasi-monochromatic X-ray at IAP NASU

3D model and a general view of the quasimonochromatic X-ray source with ion excitation.

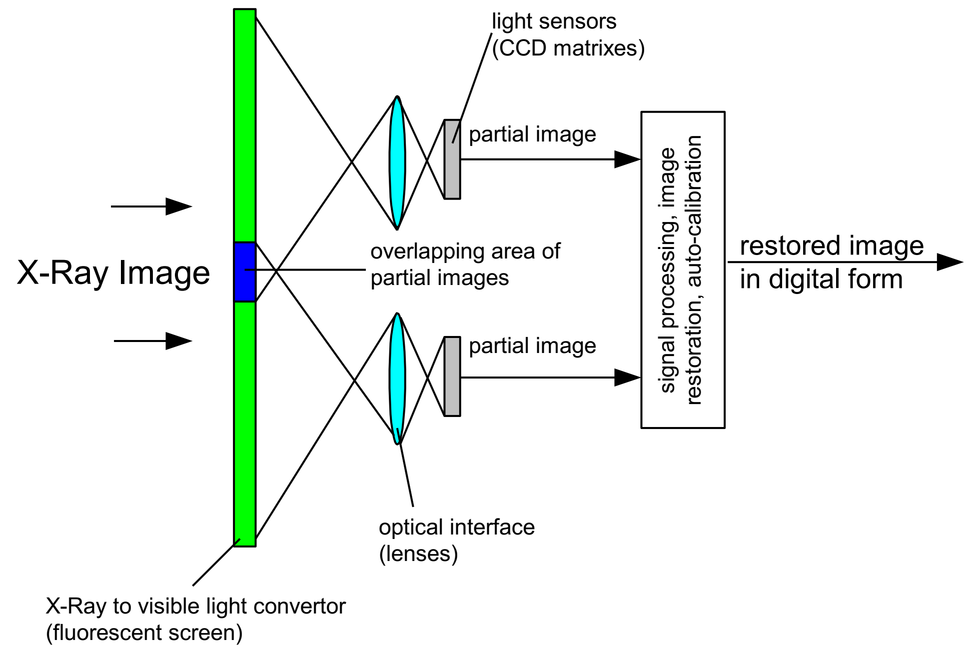




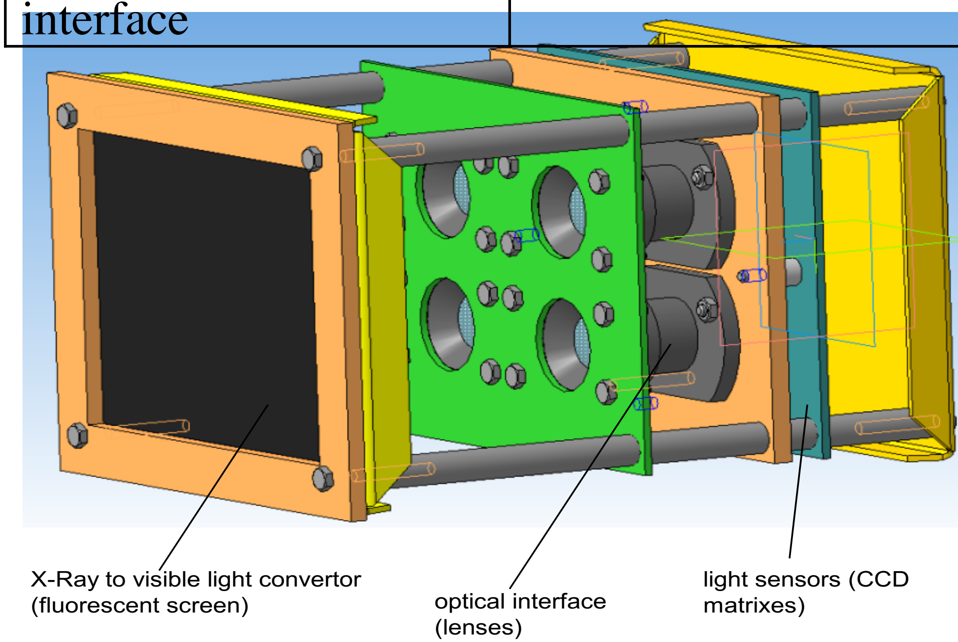
Multimatrix X-Ray detector
for phase contrast imaging experiments

Basic parameters

Sensitive Area	90x60mm
Optical Configuration	2x2 cells
DQE(0)	0.44
Optical Resolution	up to 12 pl/mm
Dynamic Range	equal to 14bits
Energy of detected X-Ray quantum	9-100keV (for different conversional screens)
Frame rate	15-150 FPS
External digital interface	Gigabit Ethernet



Optical scheme of the detector



3D CAD Driwing of the Multimatrix Hybrid X-Ray Detector

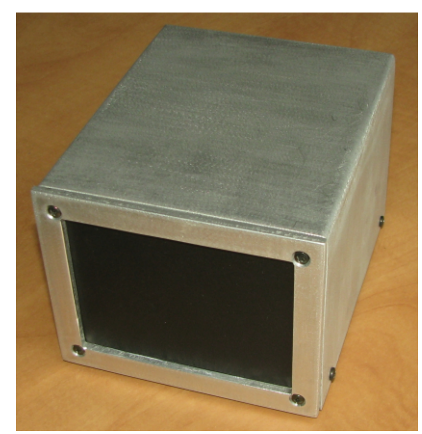


Photo of the Multimatrix Hybrid X-Ray Detector

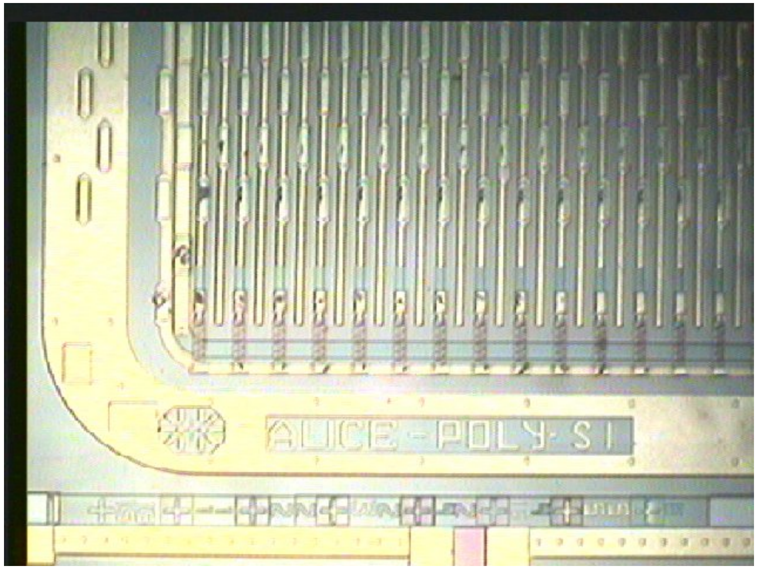
Kharkiv platform

Profile: planar detectors and dosimeters

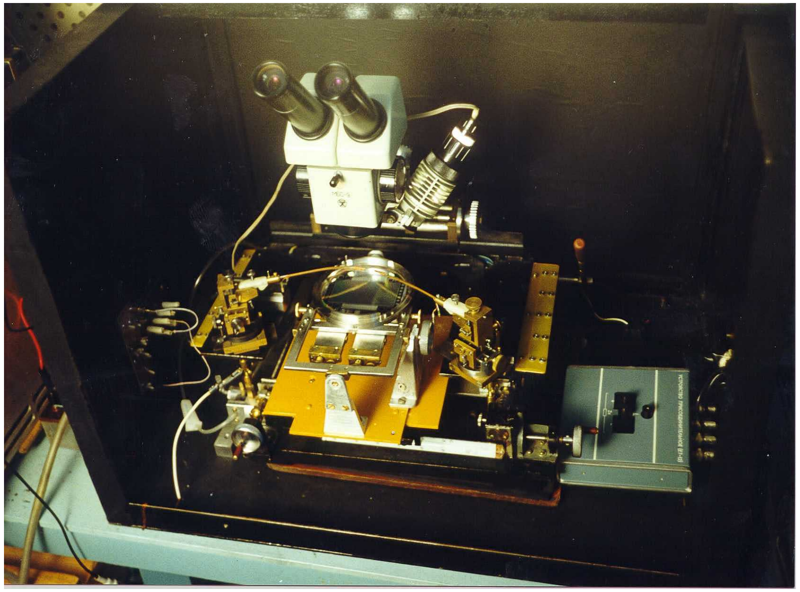
Development, installation and commissioning of microwire bonding facilities and automated facilities of detector testing

The objective	Development of a set of experimental instrumentation, techniques and versatile test platforms for development, characterization and testing of wide range of radiation detector systems
The team	N.I.Maslov (PhD) a.o., NSC KIPT, Ukraine
Expected results	Microwire bonding facilities and automated facilities for detector testing will be realized on the basis of the available facilities at KIPT and with the additionally purchased equipment. The created facilities will allow to perform a full cycle of manufacturing and automated testing of research silicon detector systems. Besides, they will allow training students in modern instrumentation and process equipment.

Double-sided (two-coordinate) microstrip detector (DSMD), produced in KIPT



Double-sided (two-coordinate) microstrip detector (628 channels on each side), constructed by Kharkiv group for HEP

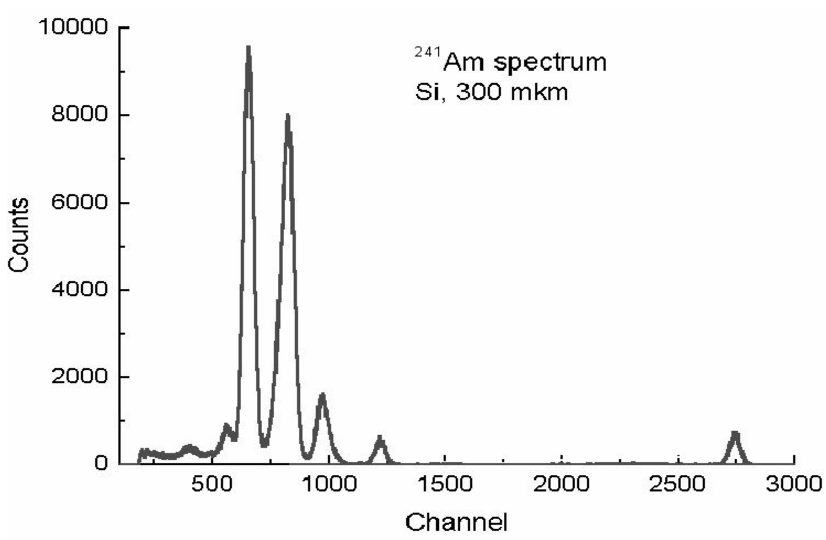


Microstrip detector in the test station with the microprobes

Single-channel and double-sided Si photosensors

The objective	Development of a set of experimental instrumentation, techniques and versatile test platforms for development, characterization and testing of wide range of radiation detector systems
The team	N.I.Maslov (PhD) a.o., NSC KIPT, Ukraine
Expected results	A single-channel double-sided silicon photosensor with its separated photosensitive and signal output functions will be realized and investigated. Using single-channel double-sided Si photosensor a scintillator-photosensor assembly will be manufactured. The spectrometric read-out system will be developed and manufactured.

Single-channel single-sided silicon spectrometer detector



Measurement of radiation of isotope source ^{241}Am using **uncooled** detector. The energy resolution of 1.16 keV. Preamplifier with resistive feedback.

Single channel silicon detector for **room-temperature** spectrometry

Specific software code for CdZnTe dosimeter

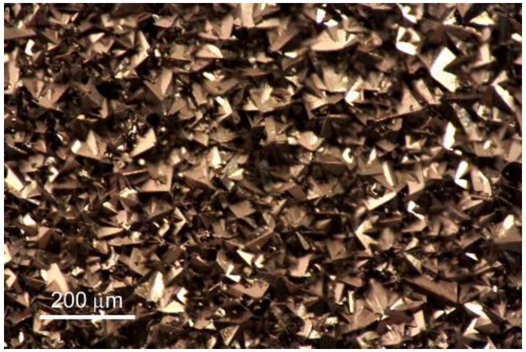
The objective	Development and characterization of CdZnTe detectors for the application in dosimetry of X- and gamma-radiation
The team	S.P.Fomin (PhD) a.o., Kharkiv National University, Ukraine
Expected results	Specific software code for CdZnTe dosimeter allowing for an analysis of the X-ray spectra will be written, verified and tested

CVD diamond detectors for dosimetry of X-ray and electron therapy beams

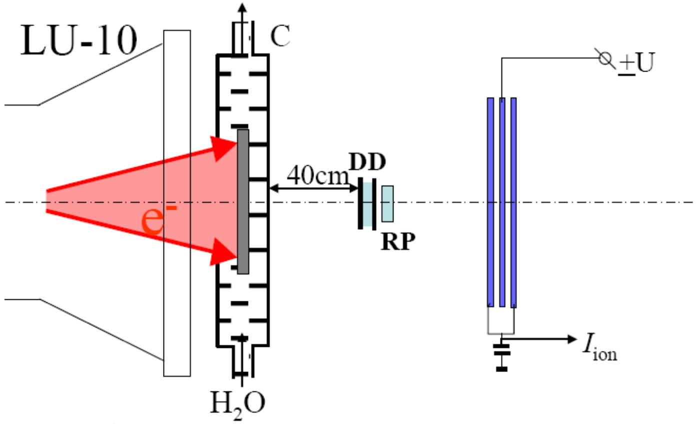
The objective Development and characterization of CVD polycrystalline diamond detectors for the application in dosimetry of X-ray and electron therapy beams

The team V.E.Kutny (PhD) a.o., NSC KIPT, Ukraine
http://www.kipt.kharkov.ua/kipt_sites/isspmst/nrdetectors/en/detectors/diamond/

Expected results CVD polycrystalline and single crystal diamond prototype detectors will be manufactured. Their parameters and properties will be investigated and irradiation tests under X-ray and electron and proton beams will be conducted.



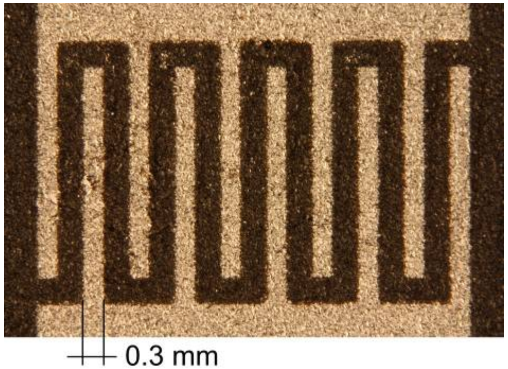
Polycrystalline diamond film grown on a silicon substrate



Calibration of diamond detector in X-ray radiation field

Their compliance with the requirements for external beam radiotherapy detectors will be determined. The response to proton beam will also be investigated.

L.N.Davydov, et al.. SPIE Proceedings, Vol. 8507, p. 85071N-1, 2012.
V.E. Kutny, et al., Problems of atomic science and technology. No. 3(91), (62), 2014. p.162.



Interdigitated Al contacts on the growth surface of the diamond film

Dosimetry of X- and gamma-radiation and electron therapy beams

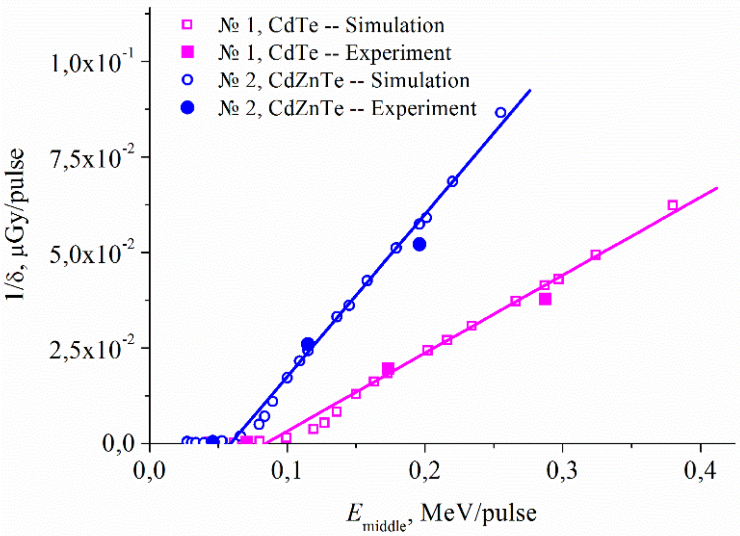
CdZnTe detectors for dosimetry of X- and gamma-radiation

The objective Development and characterization of CdZnTe detectors for the application in dosimetry of X- and gamma-radiation

The team V.E. Kutny (PhD) a.o., NSC KIPT, Ukraine
http://www.kipt.kharkov.ua/kipt_sites/isspmst/nrdetectors/en/detectors/

Expected results A prototype dosimetric device will be created, in which for precision measurements of the dose (dose rate) statistical parameters of gamma-radiation spectra will be used.

A limiting relation between transfer parameters of electrons and holes in CdZnTe detectors will be determined, beyond which the realization of the proposed method will be possible. The technique of calibration and metrological tests of the developed dosimeter will be developed.



Relation between CdTe and CdZnTe detector sensitivities and average amplitude of pulses created in detectors at the registration of gamma-quanta.

A. V. Rybka et al. Nucl. Instr. & Meth. A, 2004, vol. 531, pp.147-156.
A. Zakharchenko et al. Proc. SPIE, Vol. 8507, Paper 85071I, 2012.
A. A. Zakharchenko et al. // Proc. SPIE, Vol. 8852, Paper 88521B, 2013.

Thank you very much for your attention!!