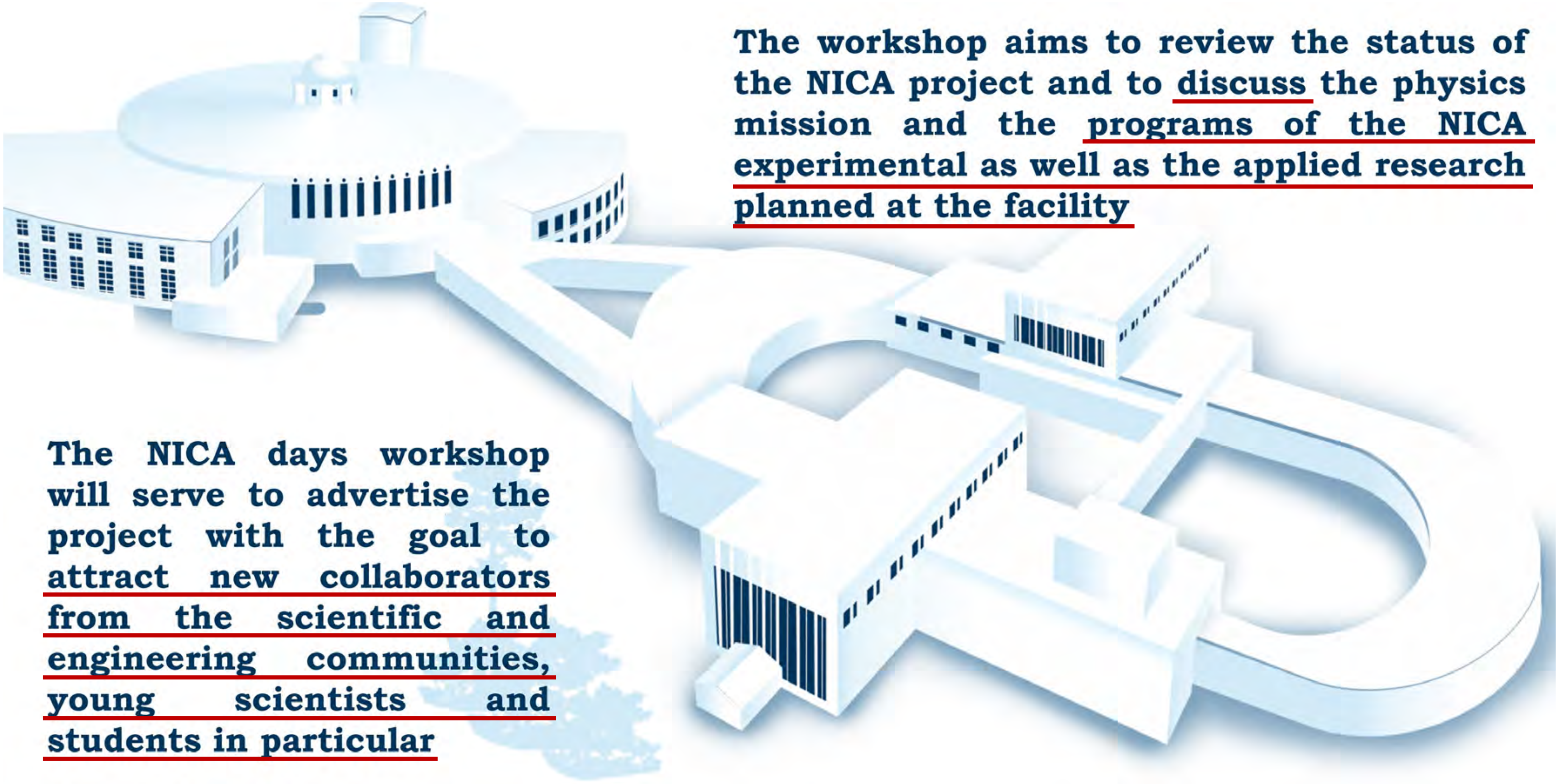
ARIADNA project:

Gates for cooperation in applied research at NICA

Oleg Belov

Veksler and Baldin Laboratory of High Energy Physics
Joint Institute for Nuclear Research
E-mail: oleg.belov@jinr.int

MISSION FOR TODAY



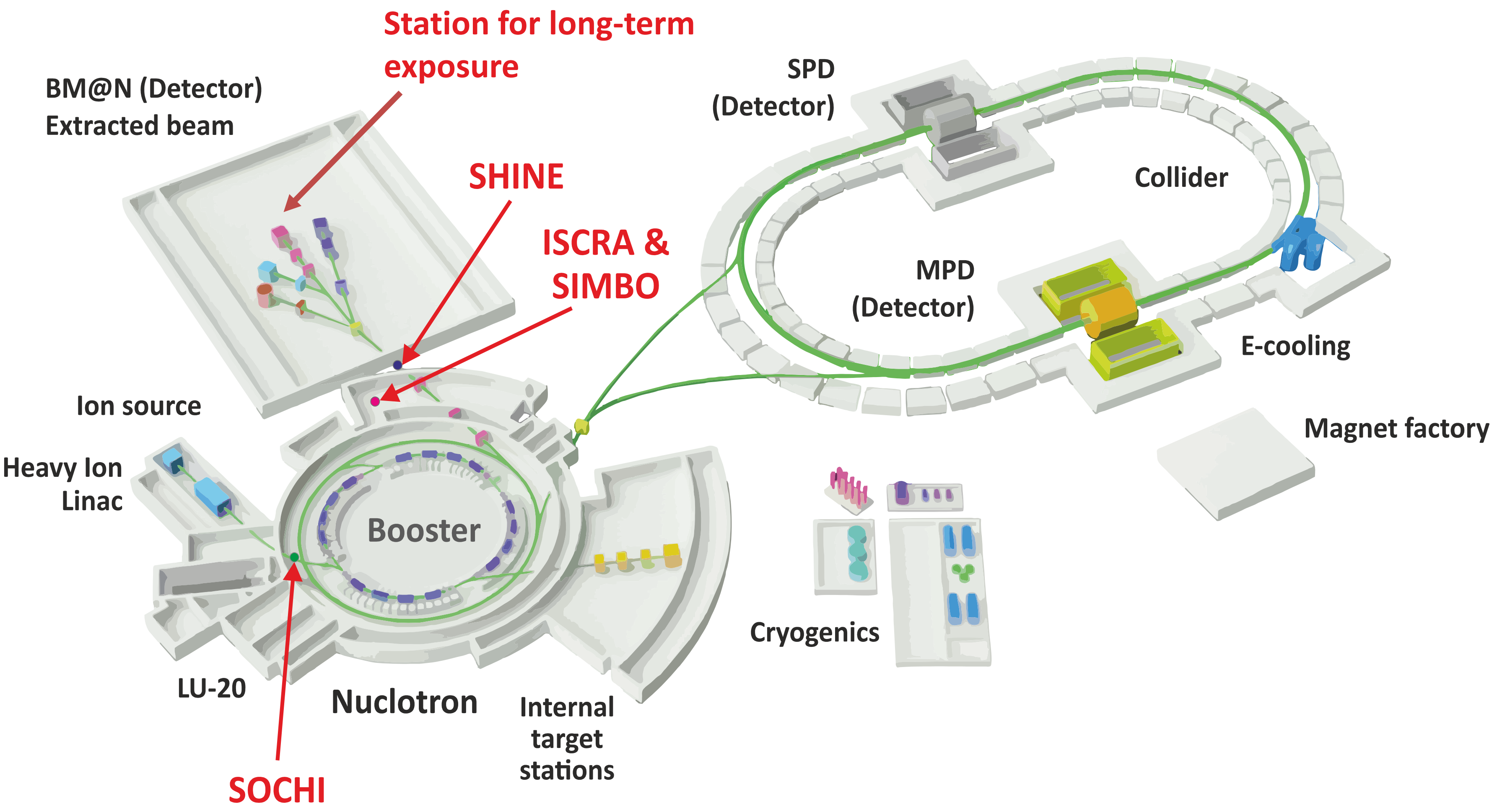
The workshop aims to review the status of the NICA project and to discuss the physics mission and the programs of the NICA experimental as well as the applied research planned at the facility

The NICA days workshop will serve to advertise the project with the goal to attract new collaborators from the scientific and engineering communities, young scientists and students in particular

Applied Research and Innovations @ NICA

The Applied Research Infrastructure for Advanced Developments at NICA fAcility (ARIADNA)

ARIADNA
beamlines



Applied Research and Innovations @ NICA

The Applied Research Infrastructure for Advanced Developments at NICA fAcility (ARIADNA) will include:

(1) Beamlines with magnetic optics, power supplies, beam diagnostics systems, cooling systems, etc.

(2) Experimental zones equipped with target stations for users (detectors, sample holders, irradiation control and monitoring system, etc.)

(3) Supporting user infrastructure (areas for deployment of user's equipment, for sample preparation and post-irradiation express analyses, etc.)

Low-energy ion beams available at HILAC 3.2 MeV/nucleon	Intermediate-energy ion beams available at Nuclotron 150-1000 MeV/nucleon	High-energy ion beams available at Nuclotron up to 4.5 GeV/nucleon
Life sciences, Radiation damage to microelectronics, Materials science, Novel relativistic nuclear technology		

Protons and ions with Z = 2 to 92

Irradiation of decapsulated microcircuits and solid materials with 3.2 MeV/nucleon ions.

Ions: $^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{56}Fe^{26+}$, $^{84}Kr^{36+}$, $^{131}Xe^{54+}$, $^{197}Au^{79}$

Irradiation of capsulated microcircuits with 150-350 MeV/nucleon ions. Ions like $^{197}Au^{79+}$ are decelerated in the capsule to 5-10 MeV/nucleon.

500-1000 MeV/nucleon ions be available at the target station for biological sample irradiation.

Ions: $^{1}H^{1+}$, $^{2}D^{1+}$, $^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{7}Li^{3+}$

Target station will be equipped with targets from C to Pb and with the systems of beam and target diagnostics, positioning, thermometry, synchronization, radiation control, and data acquisition.

ARIADNA COLLABORATION TODAY

ARIADNA-LS Collaboration	ARIADNA-MSTE Collaboration	ARIADNA-NPT Collaboration
The Collaboration is being established in order to perform experiments in the field of **life sciences** at the NICA Complex with the ARIADNA beamlines	The Collaboration is being established in order to perform activities and experiments in **radiation materials science and radiation testing of electronics** at the NICA Complex with the ARIADNA beamlines	The Collaboration is being established in order to facilitate **study of accelerator driven subcritical reactor systems** with the use of ARIADNA beamlines

Collaborating organizations

1. Joint Institute for Nuclear Research (Dubna, Int.)
2. Institute of Biomedical Problems, RAS (Moscow, Russia)
3. Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency (Moscow, Russia)
4. Skobeltsyn Research Institute of Nuclear Physics, Moscow State University (Dubna, Russia)
5. Saint Petersburg State University (Saint Petersburg, Russia)
6. Tsyb Medical Radiological Research Centre (Obninsk, Russia)
7. Semenov Research Center of Chemical Physics, RAS (Moscow, Russia)
8. Institute of Theoretical and Experimental Biophysics, RAS (Moscow, Russia)
9. Moscow Institute of Physics and Technology (Dolgoprudny, Russia)
10. Kurnakov Institute of General and Inorganic Chemistry, RAS (Moscow, Russia)
11. National Research Nuclear University MEPhI (Moscow, Russia)
12. Joint Institute of High Temperatures, RAS (Moscow, Russia)
13. North Ossetian State University (Vladikavkaz, Russia)
14. Institute of Nuclear Problems of the Belarusian State University (Minsk, Belarus)
15. CANDLE SRI, Yerevan, Armenia
16. Yerevan State University, Yerevan, Armenia
17. A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute), Yerevan, Armenia
18. Omsk State University,Omsk, Russia
19. LLC Research and production company “Kvant-R” (Moscow, Russia)
20. LLC “S-Innovations” (Moscow, Russia)
21. LLC “SOL-Instruments” (Minsk, Belarus)

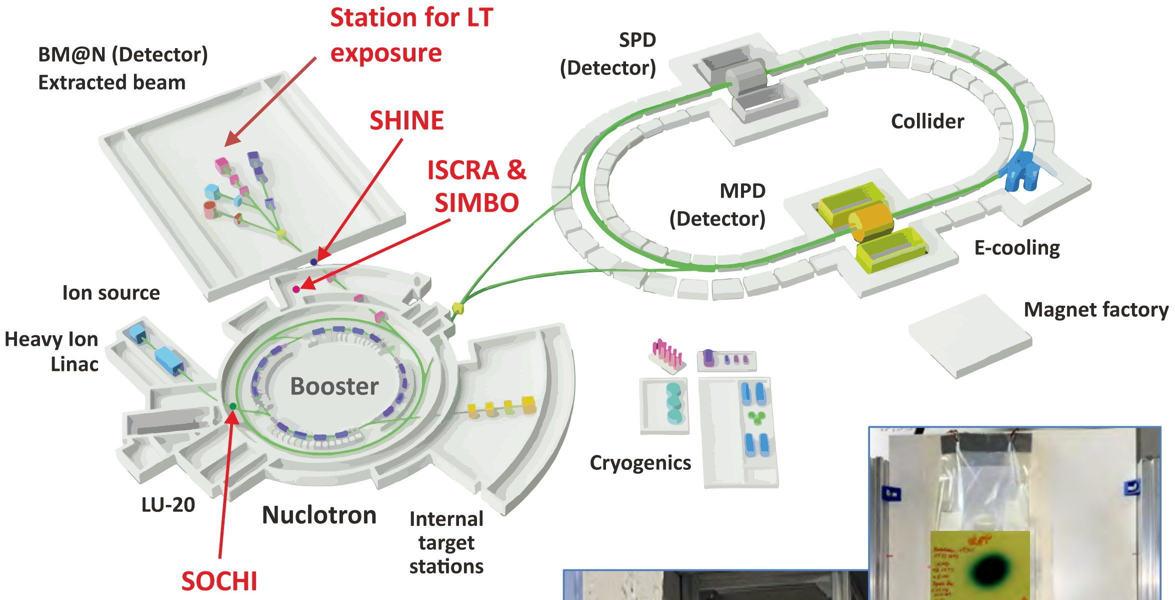
162 participants

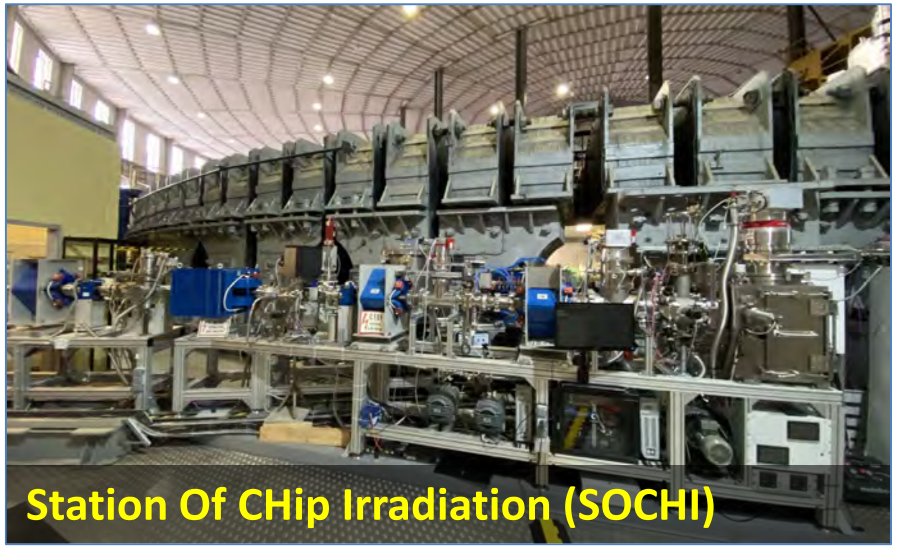
ARIADNA RESEARCH INFRASTRUCTURE: CURRENT STATE AND RECENT DEVELOPMENTS

In December 2021, the beamline and **Station Of CHip Irradiation (SOCHI)** was completed.

In December 2022, the **prototype of the Target station for long-term exposure with high energy ions** was assembled at the outgoing beam available behind the BM@N facility. This target station has an advantage to use beams for applied research purposes in parallel with operation of the BM@N setup.

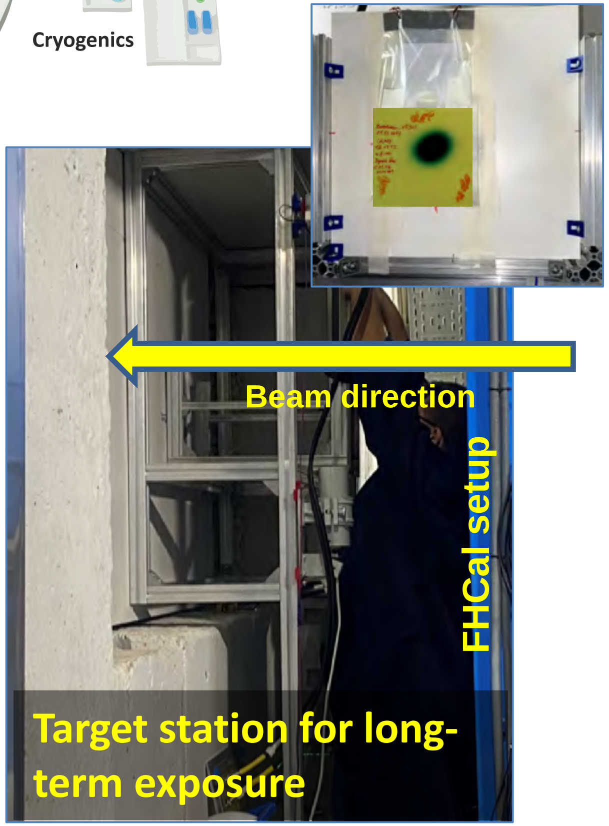
The infrastructure of **SIMBO** and **ISCRA** beamline zones are close to completed (beamlines are still in progress).





Station Of CHip Irradiation (SOCHI)

SIMBO and ISCRA target stations



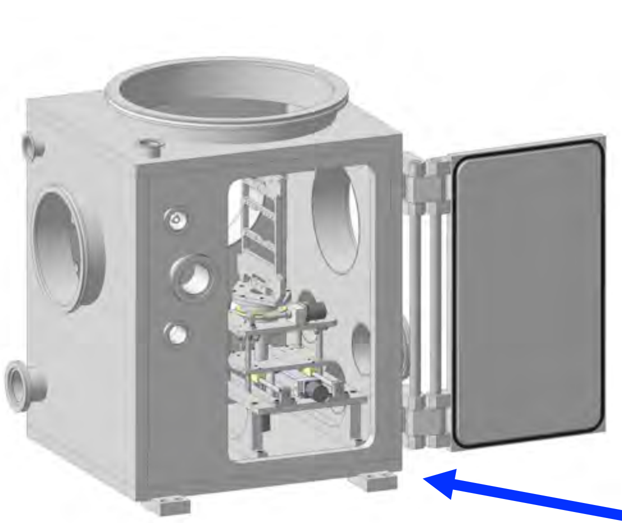
Target station for long-term exposure

LOW-ENERGY TARGET STATION FOR TESTING OF DECAPSULATED MICROELECTRONIC COMPONENTS

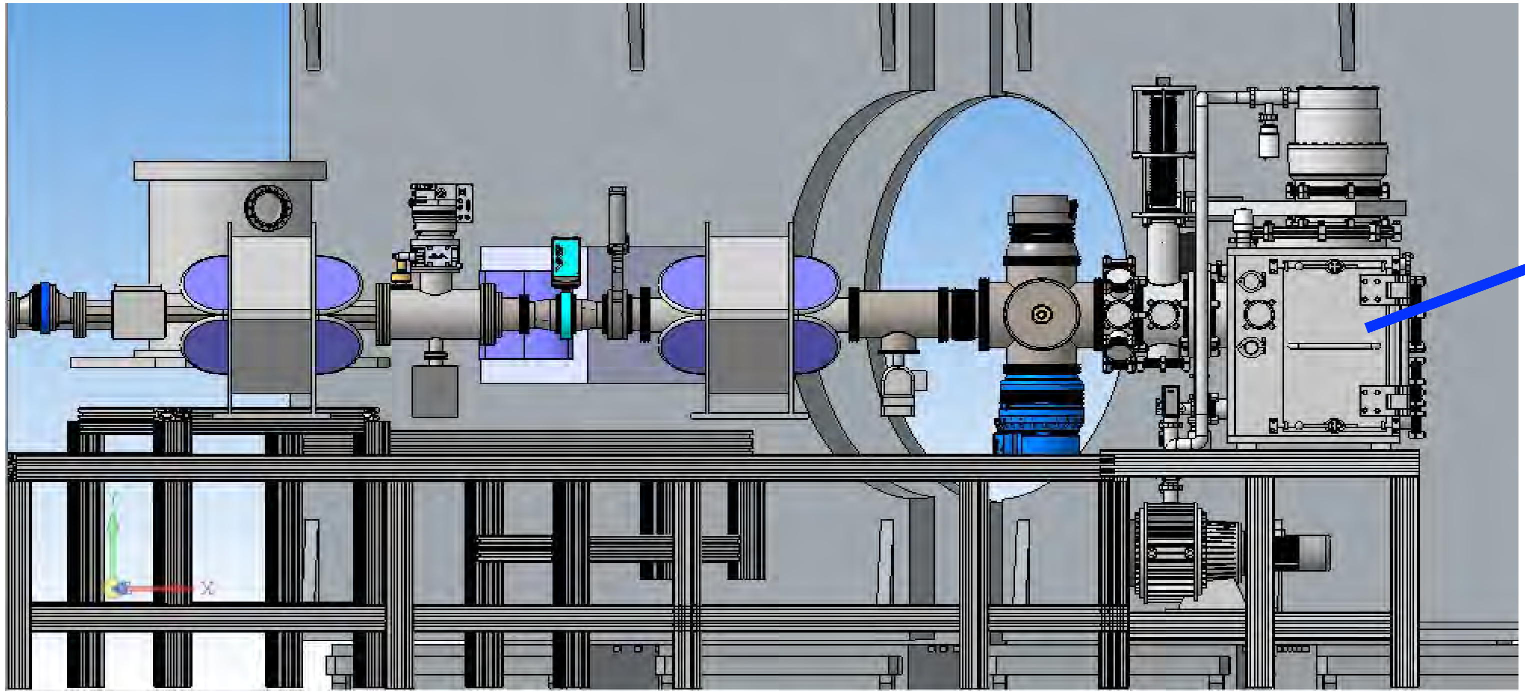
Low-energy beams extracted from the HILAC at energy 3.2 MeV/n.

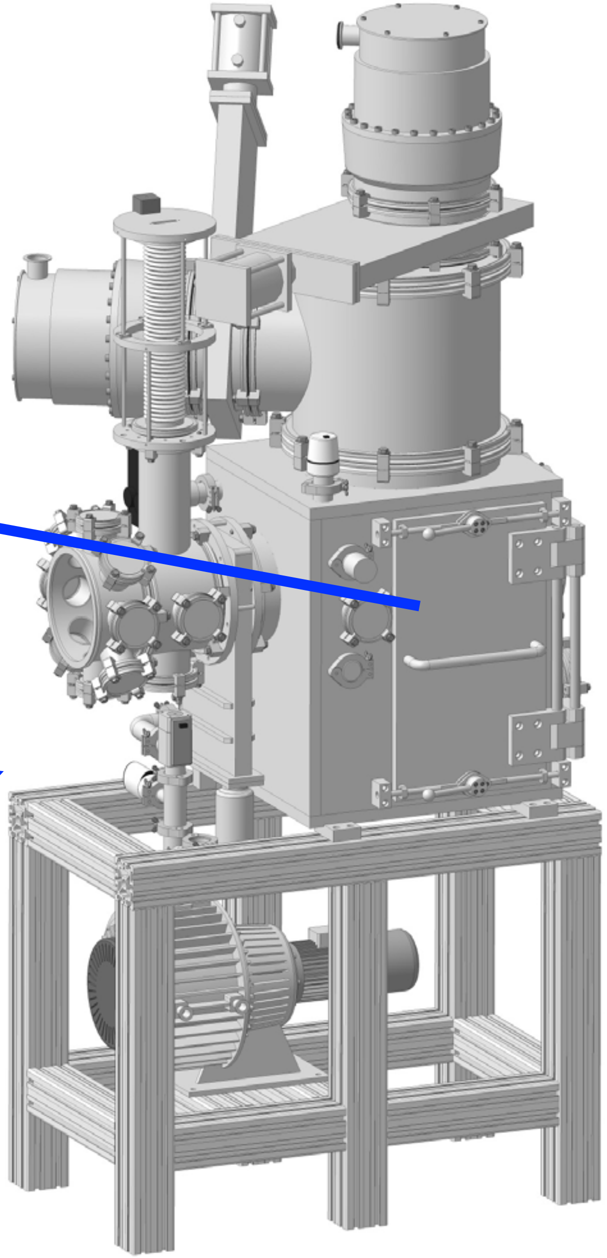
Protons and ions Z = 2 to 92.

The beamlines ands with a vacuum chamber designed for placement and online diagnostics of the microelectronic components' state.



Vacuum chamber





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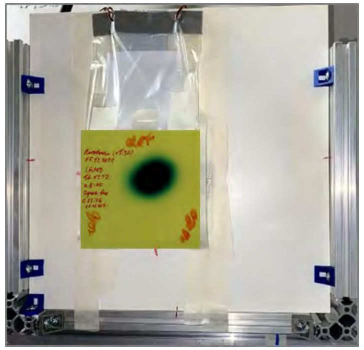
High-energy target station for long-term exposure (at the BM@N facility)

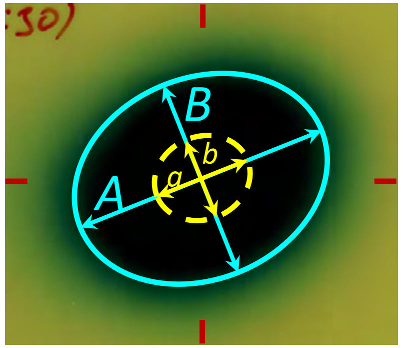
First run of the target station: 11 December 2022 – 30 January 2023

First high-energy beam for applied research at NICA

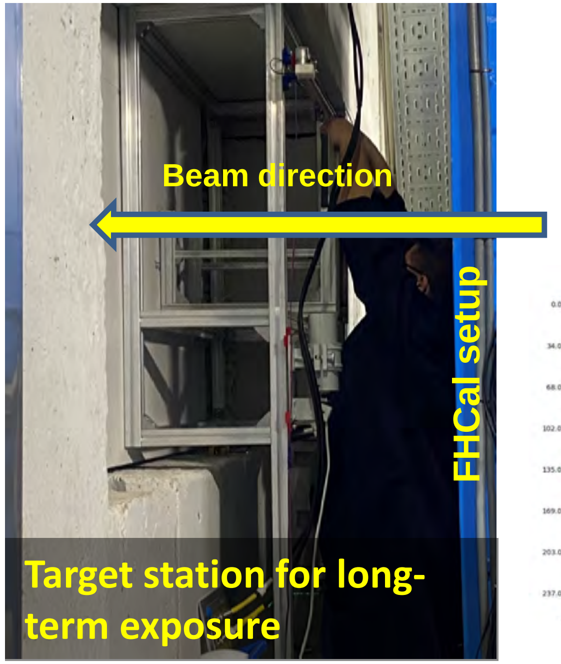


$^{124}Xe^{54+}$
3.8 GeV/nucleon

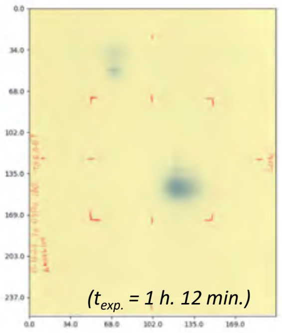
Beam trace at the EBT3 film



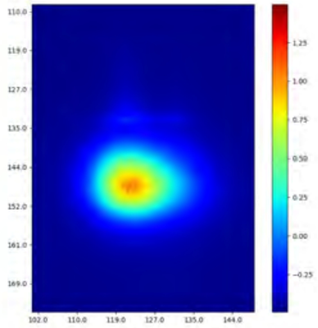
Beam parameters:
A = 34.2 mm,
B = 29.3 mm.
The most uniform area:
a = 12 mm,
b = 9 mm



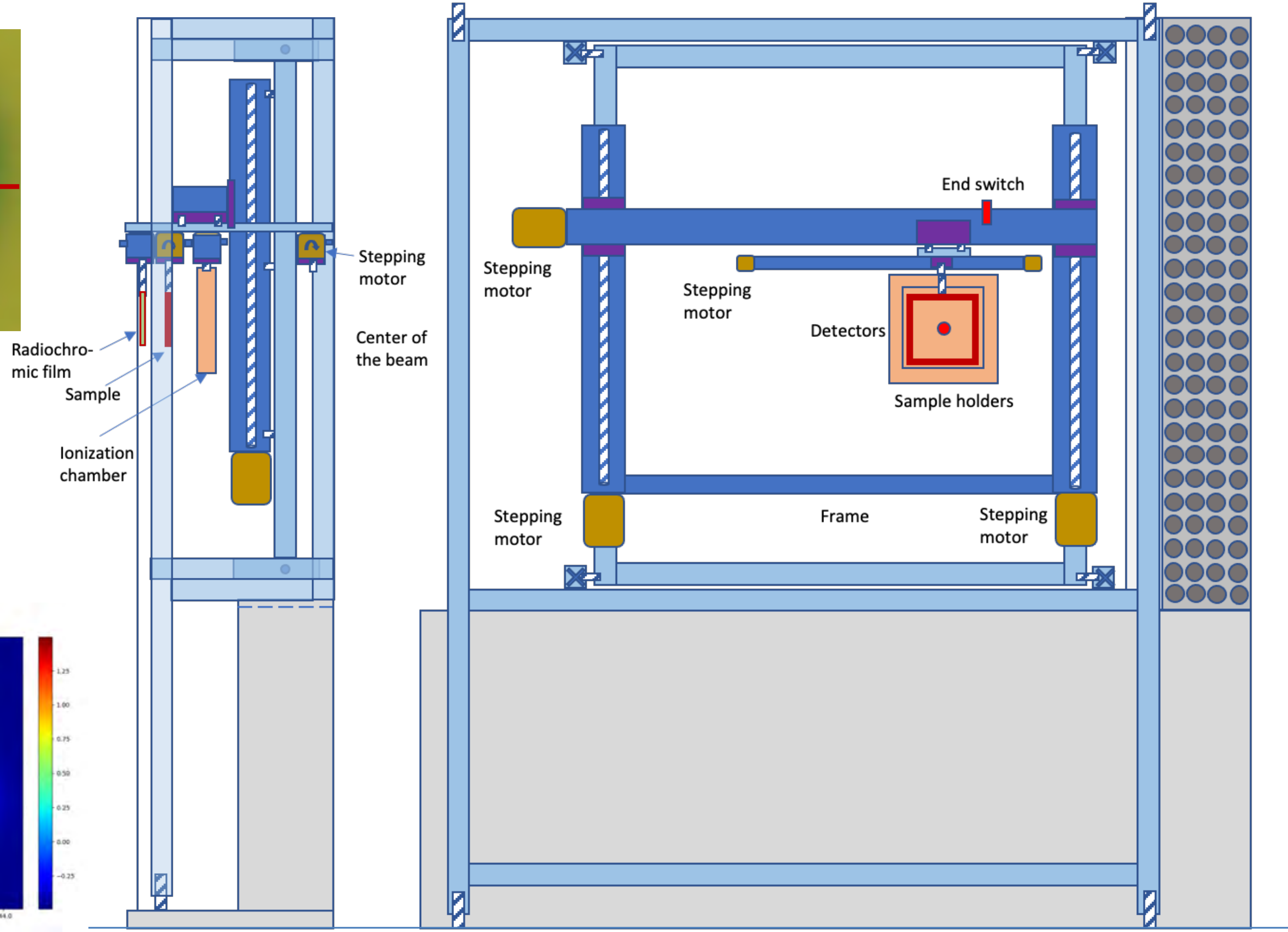
3D-map of exposure



Beam profile (EBT3 film)



Beam profile (OCTAVIUS Detector 1500 XDR)



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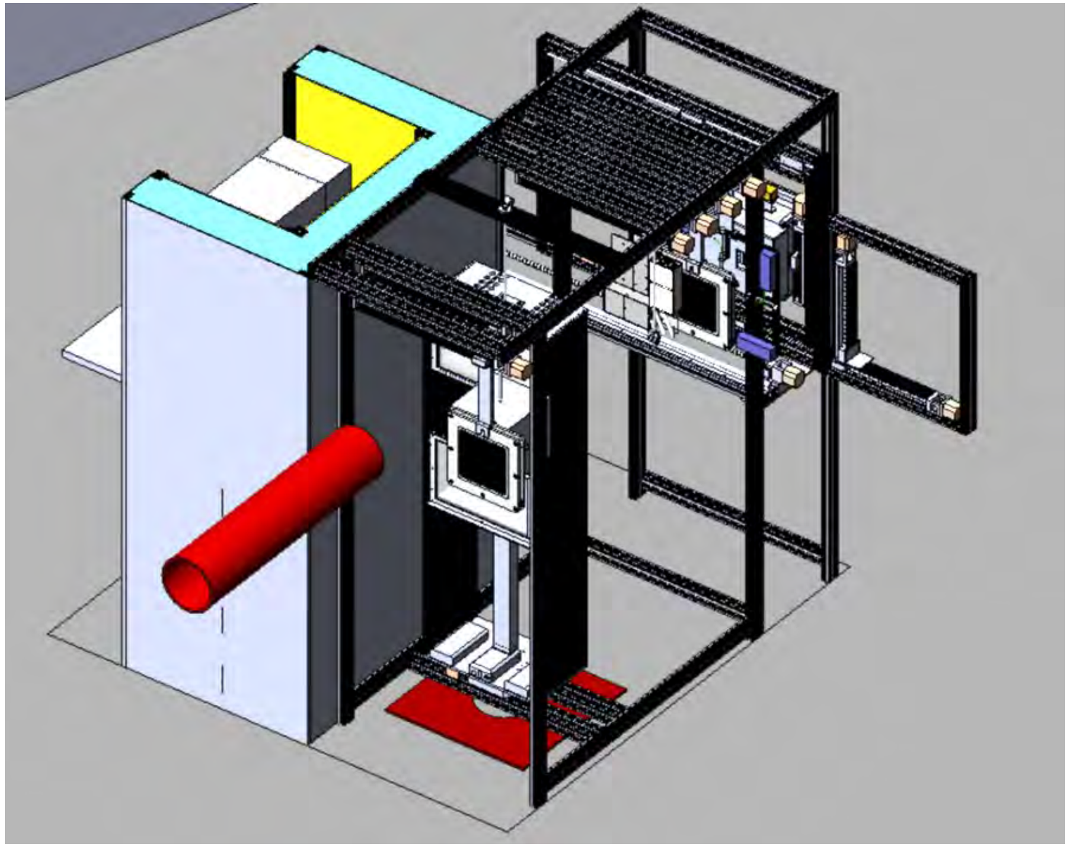
TARGET STATION FOR TESTING OF CAPSULATED MICROELECTRONIC COMPONENTS (ISCRA)

The beam diagnostic provides measurements of ion beam profiles, primary ion fluence, the primary ion density flux, the secondary particle density flux, the radiation dose: (three ionization chambers, scintillation-fiber detector, semiconductor detector, multi electrode cylinder Faraday, Si strip detector for individual ion detection, four on-line control scintillation detectors)



Beam parameters	
Ion types	$^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{56}Fe^{26+}$, $^{84}Kr^{36+}$, $^{131}Xe^{54+}$, $^{197}Au^{79}$
Ion energy, MeV/n	150-350
Ion flux density, particle/(cm²·s)	10^2 .. 1×10^5
Fluence per session, ion/(cm²)	10^7
Area of chip irradiation of 20×20 mm without scanning, mm	∅30
Flow uniformity at chip irradiation of 20×20 mm without scanning	10%
Exposure area in scan mode, mm	200×200
Flux uniformity at scan irradiation	±15%
FWHM beam diameter at target, mm	25-73
Range of LET (Si)	1…70 MeV·cm²/mg

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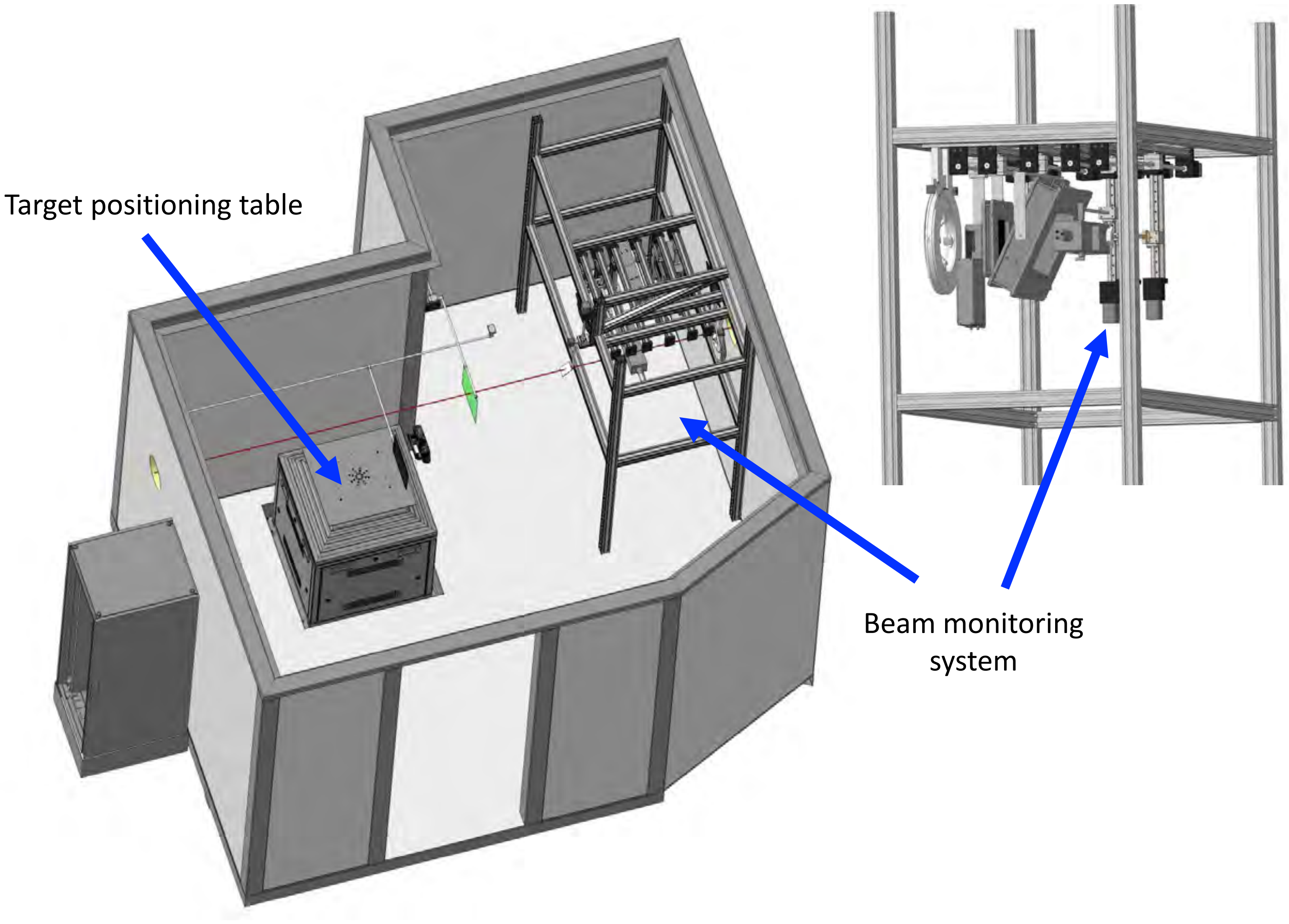
TARGET STATION FOR BIOLOGICAL OBJECTS (SIMBO)



Beam parameters

Ion types	$^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{56}Fe^{26+}$, $^{84}Kr^{36+}$
Ion energy at the exit from the Nuclotron, MeV/n	500-1000
Ion flux density, particles/(cm²·s)	$10^3..10^6$
Irradiation time per run, min	1-5
Radiation dose, Gy	1-3
Maximum irradiation area in the scanning mode/ nonscanning mode, mm	100x100/Ø10
Flux uniformity for the maximum irradiation area in the scanning mode/ nonscanning mode, %	5/10
Beam FWHM at the target, mm	25-35

The target station is located inside an artificial climate box

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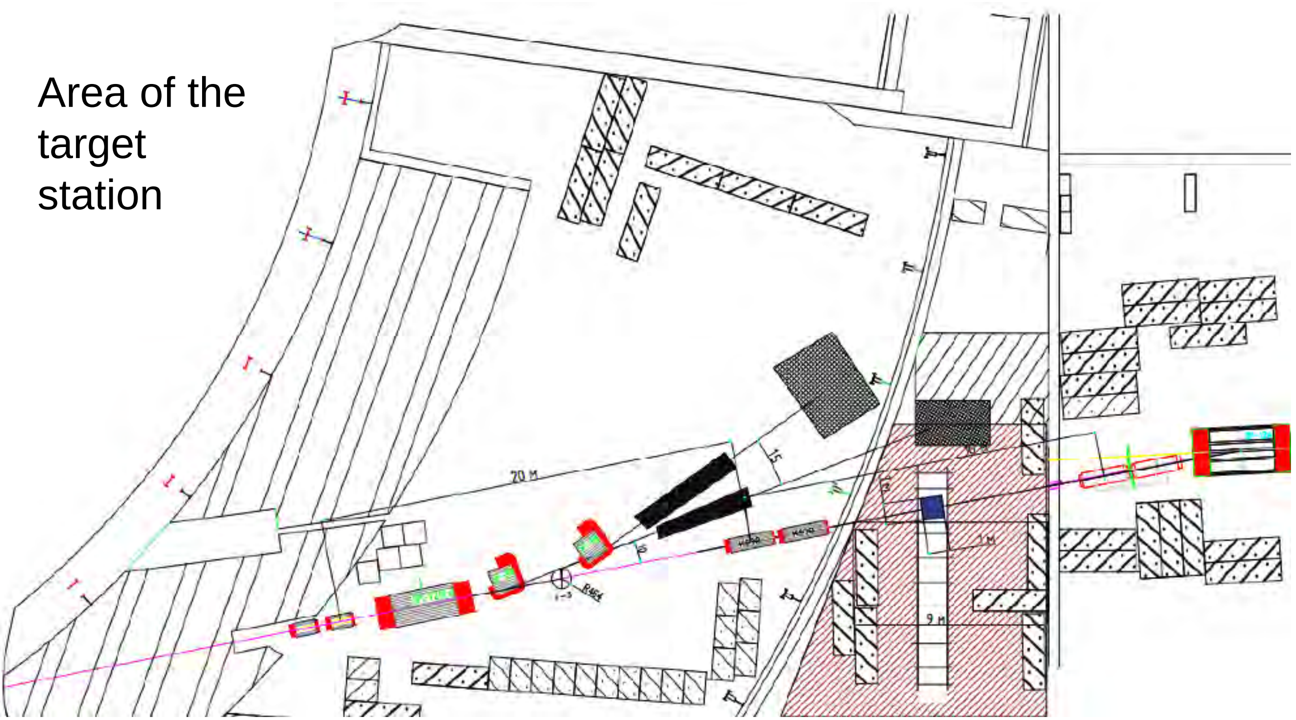
TARGET STATION FOR ADS AND RELATED APPLICATIONS (SHINE)

Area of the target station



The target station is developed for nuclear power applications and ADS. Light ion beams at energy of 0.3-4 GeV/n are planned to be used for the corresponding research program. Light ions have a short path in the target, which reduces the probability of inelastic nuclear interactions and the required beam power for ADS.

Equipment of the target station involves: targets from C up Pb at length up 1.5 m and diameter up 35 cm, thin targets from Be to U at thickness 0.05-50 mm; beam diagnostic system; target diagnostic system on base of activation and track analysis; target position system; thermometry system; synchronization system; radiation control system; data acquisition system.

S. Tiytiynnikov, M. Paraipan, A. Baldin et al.

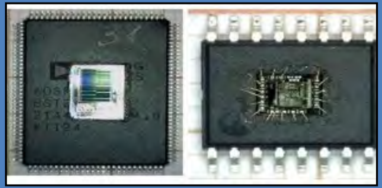
Beam parameters

Ions	$^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{7}Li^{3+}$,$^{1}p^{1+}$, $^{2}D^{1+}$
Ion energy, GeV/n	0.3-4.0
Ion intensity, 1/s	$^{1}P^{1+}$, $^{2}D^{1+}$ - 10^{10} $^{12}C^{6+}$, $^{7}Li^{3+}$ - 10^{9}
Nuclear impurities with non goal Z, %	5
Field of irradiation, mm	∅ 20-50
Fluence at irradiation of a single object	>10^{14}

The beams at this target station are also available for other directions of applied research

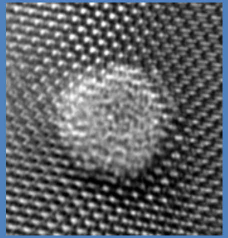
PILLARS OF APPLIED RESEARCH PROGRAMME WITH NICA BEAMS

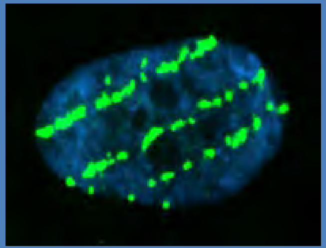
Radiation effects in microelectronics



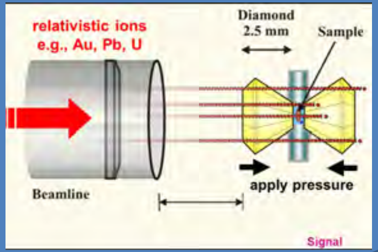
Radiation protection on Earth and in space

Materials research with ion beams

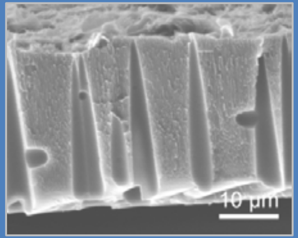


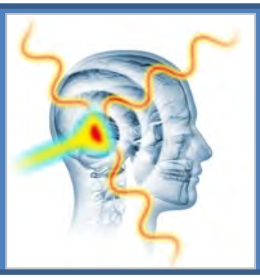


Radiation biophysics and radiobiology

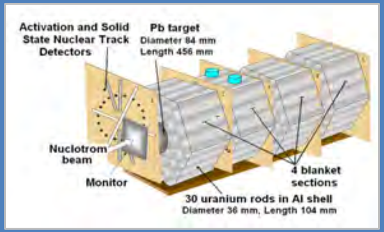


Materials in extreme radiation dose conditions





Radiation therapy-related research



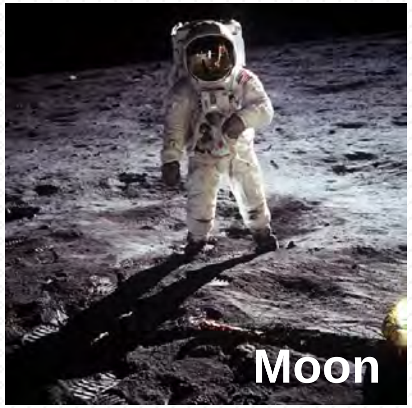
Novel technologies for accelerator-driven systems (ADS)

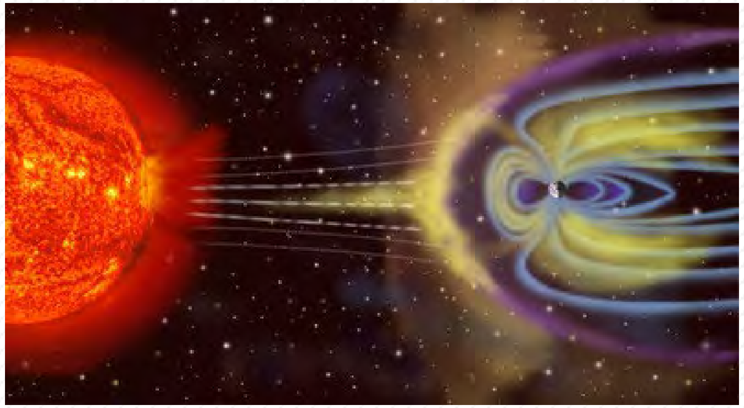
I. Space research work package

- **Simulation of space radiation components in Earth-based conditions.**
- **Characterizing the isolated risk from space radiation in both the biological and electronic contexts.**
- **Development of adequate countermeasures against the space radiation.**

The research be conducted at NICA seeks to increase the safety of space exploration through radiobiology and electronic device studies. ARIADNA will use beams of heavy ions extracted from NICA accelerators to simulate the high energy cosmic rays found in space. ARIADNA will features state-of-the-art specimen preparation resources, its own beam line dedicated to life science research and radiation hardening of space electronics. Other experiments will be focused on the use of industrial materials as samples, studying their suitability for space suits and spacecraft shielding.

Implementation of the research program in collaboration with organizations responsible for the medical care of astronauts during current manned flights and future interplanetary missions





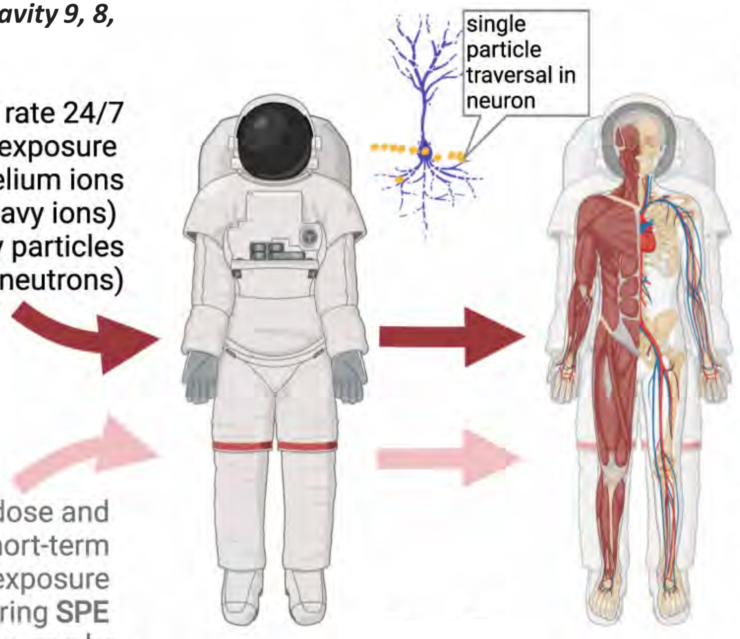
Risk assessment in long-term manned space missions

Modified from ***Fogtman et al. Nature npj Microgravity 9, 8, 2023***

Modulating effects of other spaceflight environmental factors (microgravity, sleep disturbances etc.)

Chronic low-dose rate 24/7 whole-body exposure to **GCR** (protons, helium ions and heavy ions) and secondary particles (neutrons)

Acute high-dose and high-dose rate short-term whole-body exposure during **SPE** (mostly protons, can be shielded)



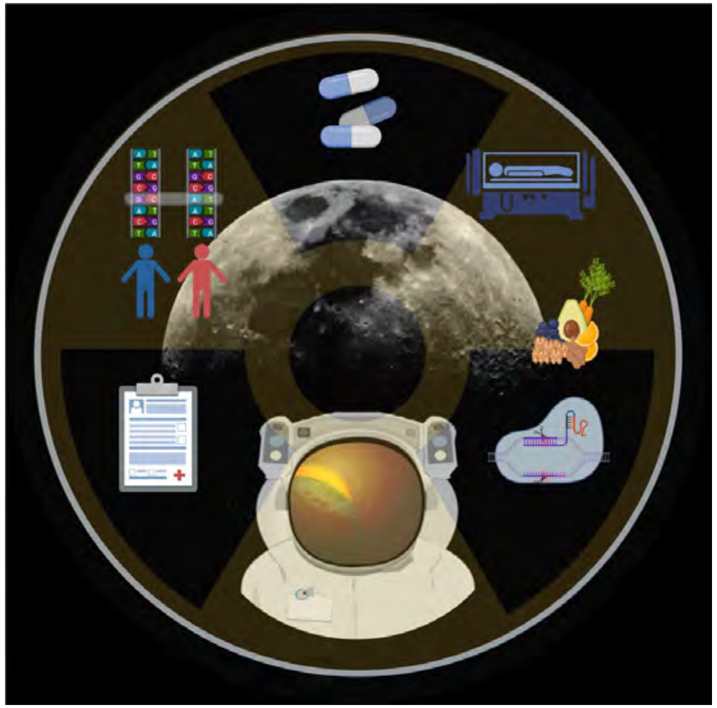
Chronic or late effects

Cancer
Cataract
Degenerative diseases of brain, lung cardiovascular, digestive endocrine, immune and reproductive systemes

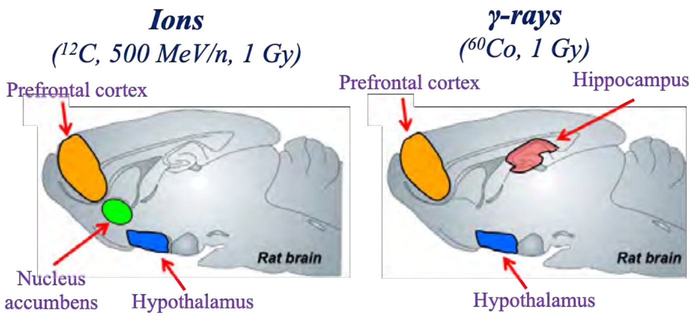
Acute effects

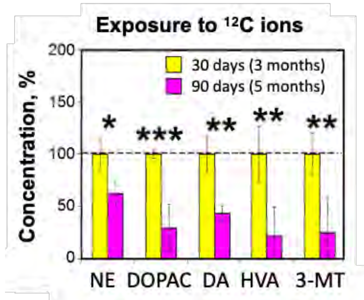
Acute radiation syndrome
- prodromal syndrome
- hematopoietic syndrome
Skin effects

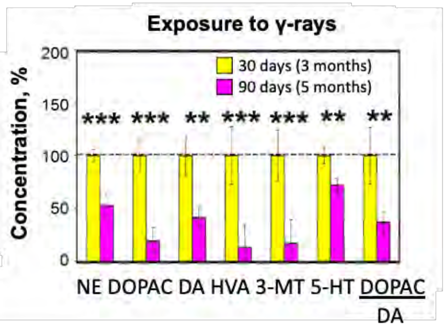
Individual differences in radiation sensitivity and susceptibility



Selection campaigns—genome-wide association studies—radioprotective pharmaceuticals—hibernation (synthetic torpor) —food supplements—genome editing.

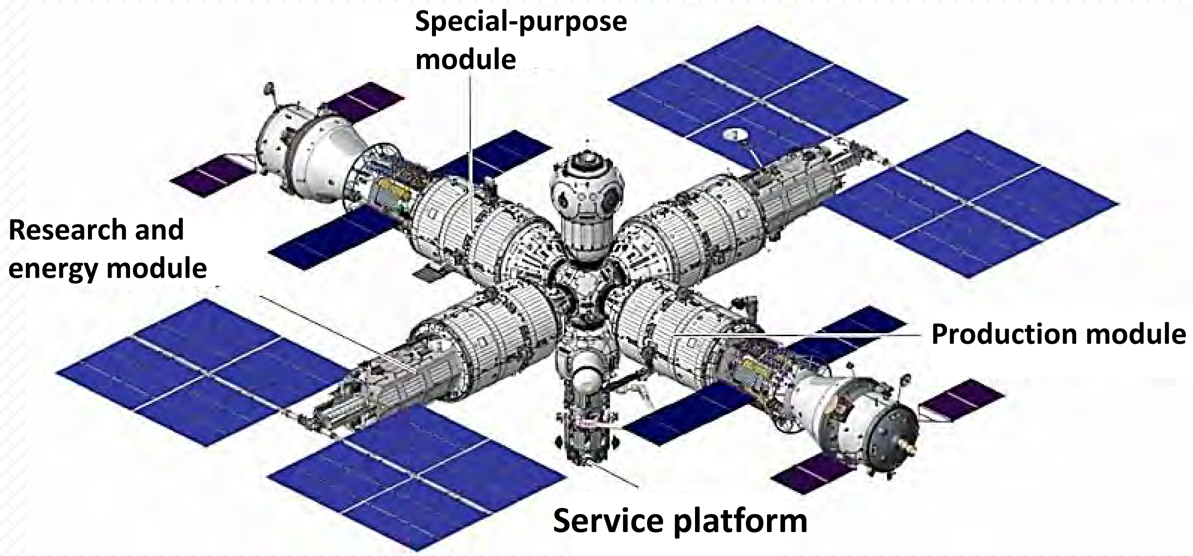






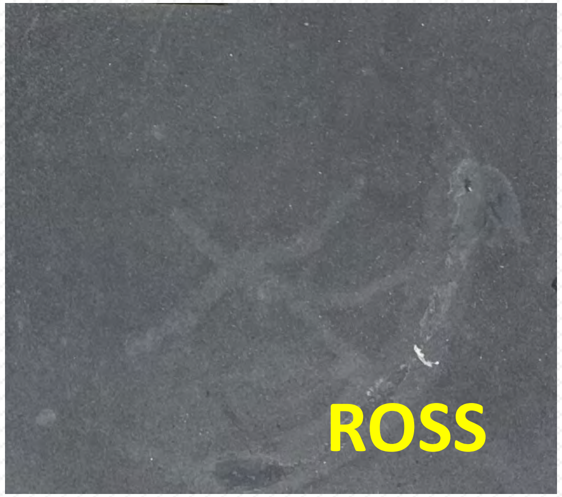
New composite materials for space industry (protective properties, radiation resistance, radiation-induced modification)

- Improving the regular means of radiation protection in spacecrafts for orbital flights and missions beyond the Earth magnetosphere.
- Study of shielding properties of existing and new composite materials.
- Investigation of radiation modification of composite materials by high-energy accelerated ion beams during long-term irradiation.

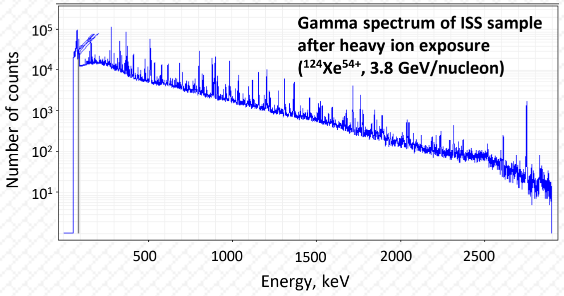


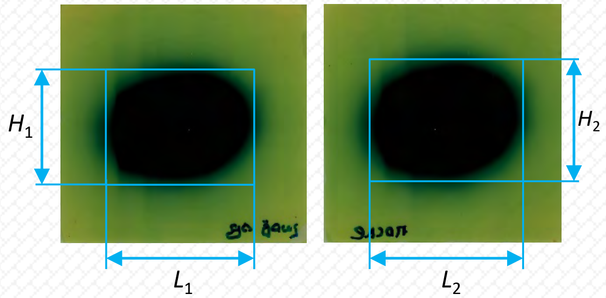
Project of the new Russian Orbital Service Station (ROSS)

Shielding material from the International Space Station (ISS)



New shielding material for the future Russian Orbital Service Station (ROSS)

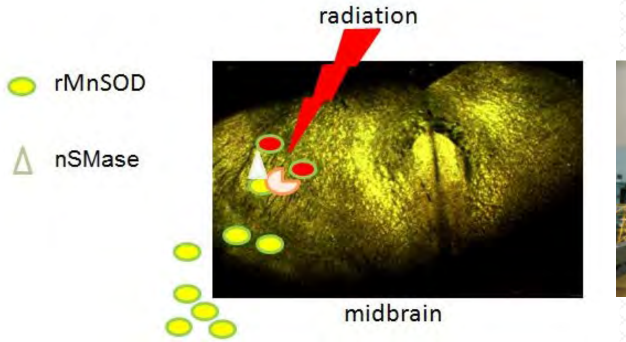




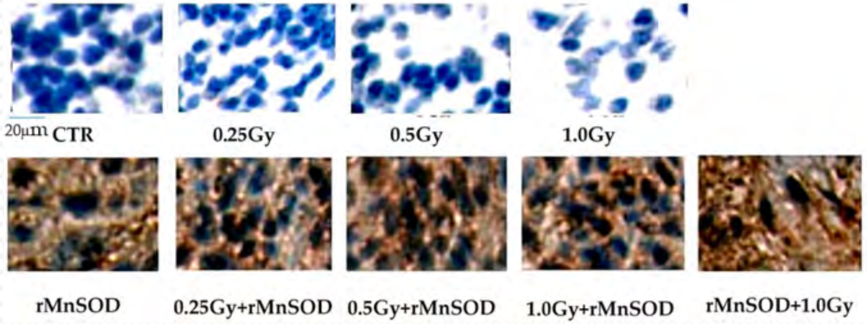
- ❑ Structural, chemico-physical methods of research and testing.
- ❑ Comparative studies under the influence of other types of ionizing radiation.

Radiation protection in space: Pharmaceutical correction

Development and testing of pharmaceuticals for protecting astronauts from space radiation on experimental models of laboratory animals



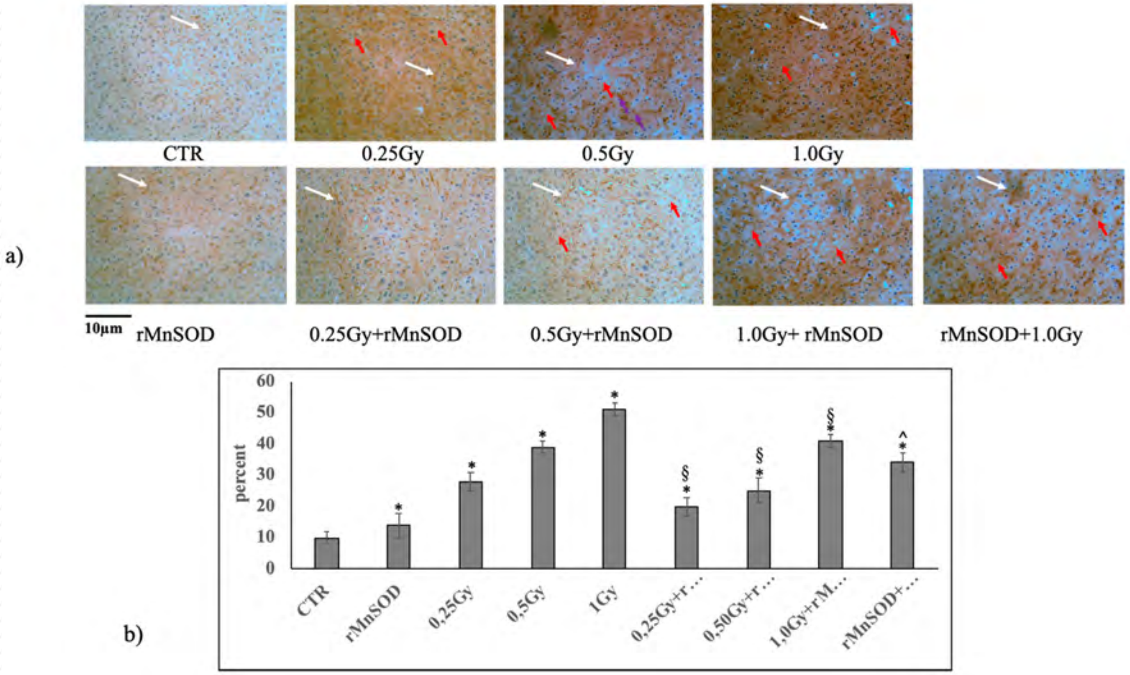
It has been established that recombinant human manganese-containing superoxide dismutase (rMnSOD), which has specific antioxidant and antiradical activity, is able to overcome the blood-brain barrier and penetrate into the midbrain, preventing radiation damage.



Localization of rMnSOD in brain tissue. Immunohistochemical analysis was performed by using specific antibody. The immunostaining was evident only in brain samples from rMnSOD-treated mice.

Cataldi, S.; Borrelli, A.; Ceccarini, M.R.; Nakashidze, I.; Codini, M.; Belov, O.; Ivanov, A., et al. Neutral Sphingomyelinase Modulation in the Protective/Preventive Role of rMnSOD from Radiation-Induced Damage in the Brain. Int. J. Mol. Sci. 2019, 20, 5431.

The ability of rMnSOD to reduce radiation-induced damage has been shown, both through a protective role associated with sphingomyelinase with an acidic pH optimum (aSMase), and through a prophylactic role through sphingomyelinase with a neutral pH optimum (nSMase).



Mouse liver after irradiation with or without protective or preventive rMnSOD treatment (**a**) representative liver histology by Caspase-1 immunohistochemical staining. (**b**) Quantification of Caspase-1 staining was performed using the ImageFocus software. Positive staining is indicated as low (+), medium (++), or high (+++). Only high positive staining was considered and was measured as a percentage of the total area. Data represent the mean + S.D. of three livers for each group. Significance, * $p < 0.05$ with respect to the CTR, § $p < 0.05$ with respect to the irradiated samples, ^ $p < 0.05$ with respect to 1.0 Gy + rMnSOD.

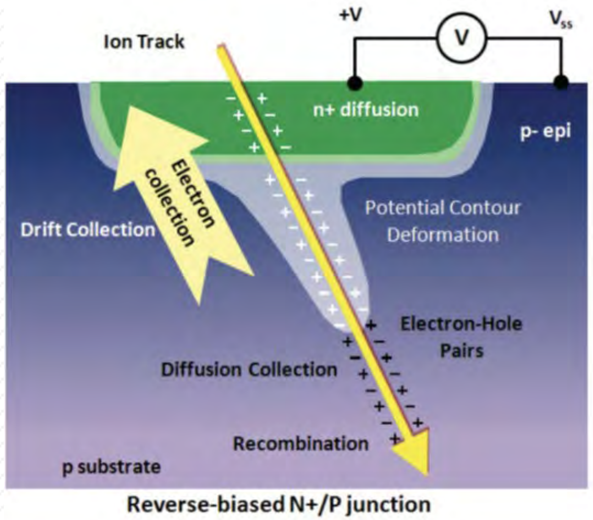
Cataldi S, Borrelli A, Ceccarini MR, Nakashidze I, Codini M, Belov O, Ivanov A, et al. Acid and Neutral Sphingomyelinase Behavior in Radiation-Induced Liver Pyroptosis and in the Protective/Preventive Role of rMnSOD. Int J Mol Sci. 2020, 21(9), 3281.

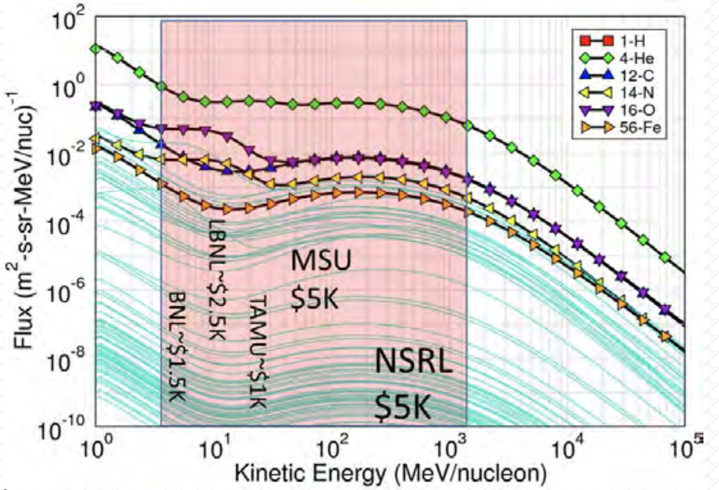
Radiation testing of electronics with ions of relatively high energy

Two types of radiation effects

- Cumulative (dose) effects result from long-term exposure to radiation environment
- Single-Event Effects (SEE) occur promptly due to a **single particle** strike

Recent studies: 25-50% of spacecraft anomalies due to SEE (depends on spacecraft orbits)



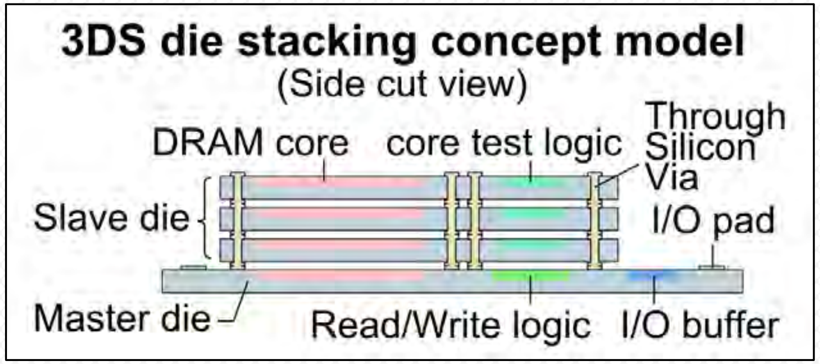


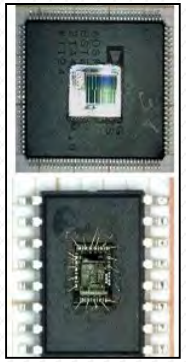
/R.C. Baumann, 2013 NSREC Short Course/

Increasing integration poses problems for SEE testing with low-energy beams

- Multiple die stacked together in packages.
- Behavior may differs if dis-assembled, tested separately.
- Packages now intrinsic to part performance.
- Dis-assembly may compromise timing, thermal and structural characteristics—especially if thinning required.

- Ideally, prefer test with ions' characteristic relevant to space
- GCR ions fairly flat out to >2 GeV/nucleon (min. ionizing)
- Difficult and expensive to achieve at accelerators





/By R.L. Ladbury at the Meeting of the American Physical Society, Columbus, OH, April 14-17, 2018/

SEE Frontiers:

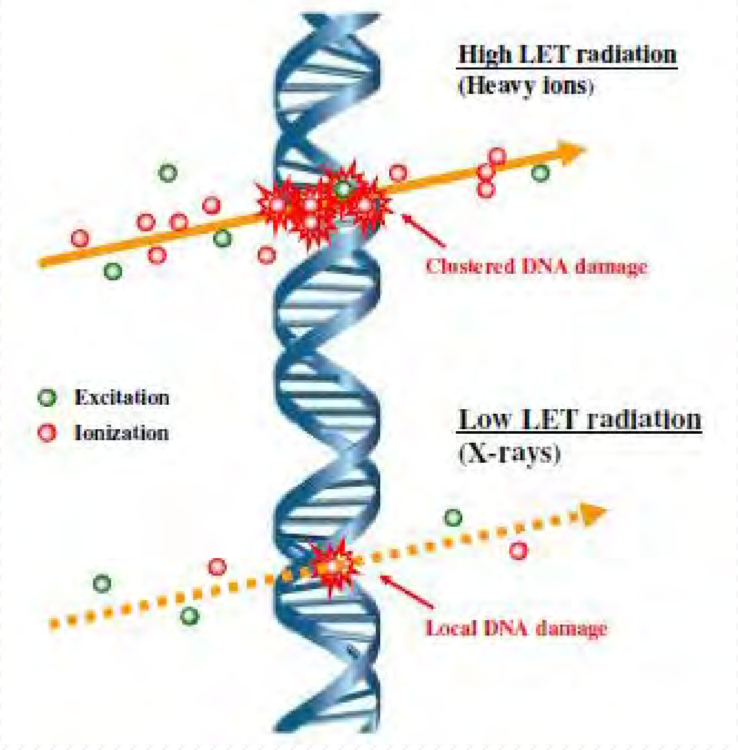
1. Technology Frontier
2. Low-Energy Frontier
3. **High-Energy Frontier – relevant to facilities like NICA**

II. Clinical work package:
DNA repair markers for cancer characterization

Studying the mechanisms and regularities of DNA repair in normal and cancer cells exposed to different types of radiation exposure (including ion beams produced by NICA facility) enables to identify specific protein markers associated with cancer.

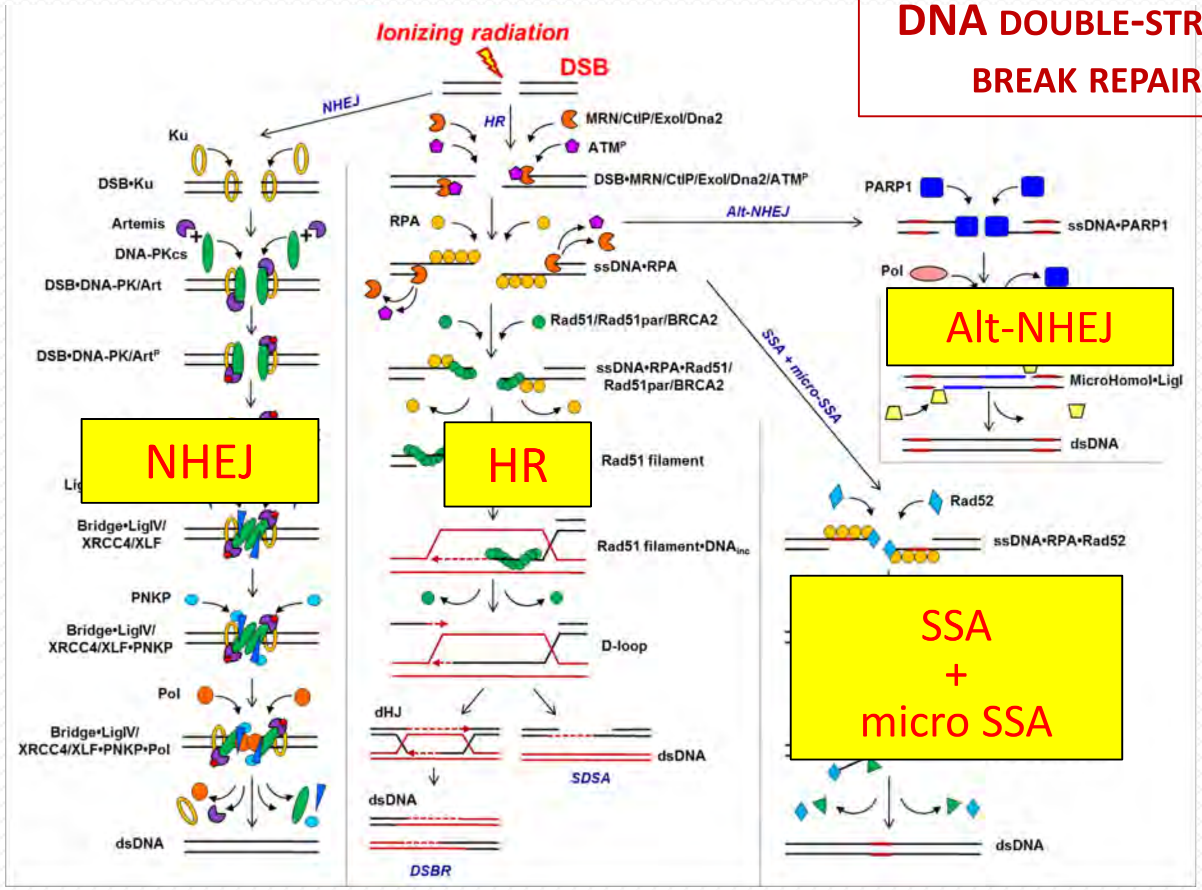
Joint project with Instituto Nacional de Cancerología (INCan, Mexico)

Radiation-induced DNA damage



Modified from W. Tinganelli and M. Durante. Carbon Ion Radiobiology. Cancers 2020, 12, 3022

DNA double-strand break repair



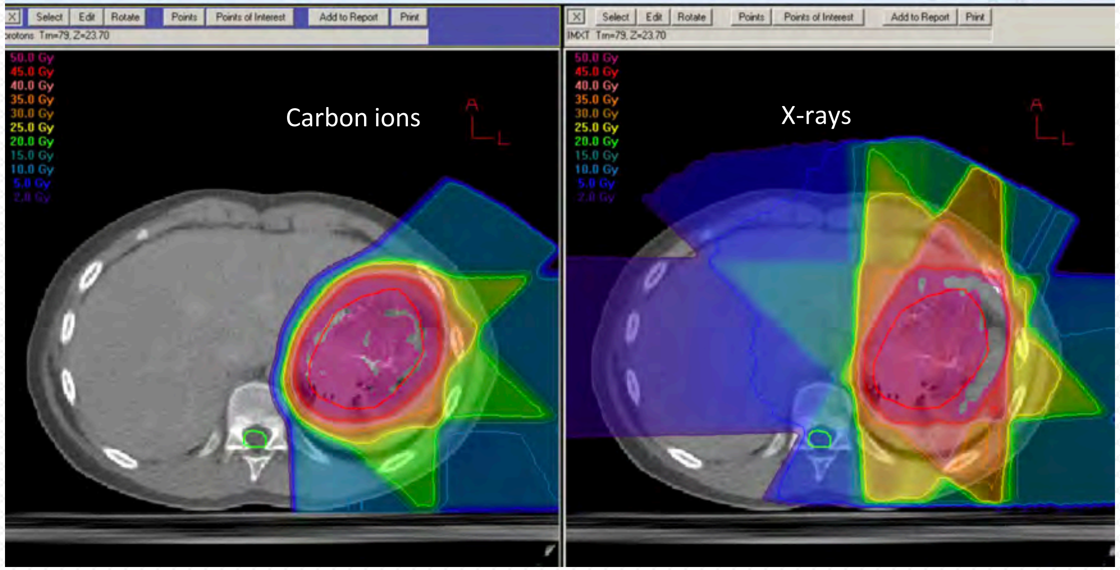
Modified from O. Belov et al., 2015–2023

Improvement of radiotherapy techniques

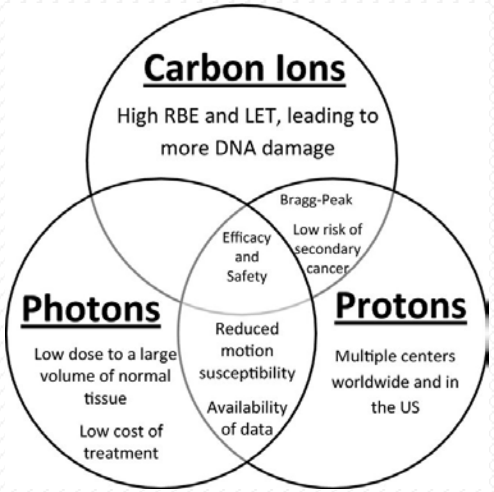
- Study of ion beam effects on redox properties and biological activity of nanoparticles of rare-earth metals in various modifications, for their further use as radioprotectors/radiosensitizers in radiotherapy.

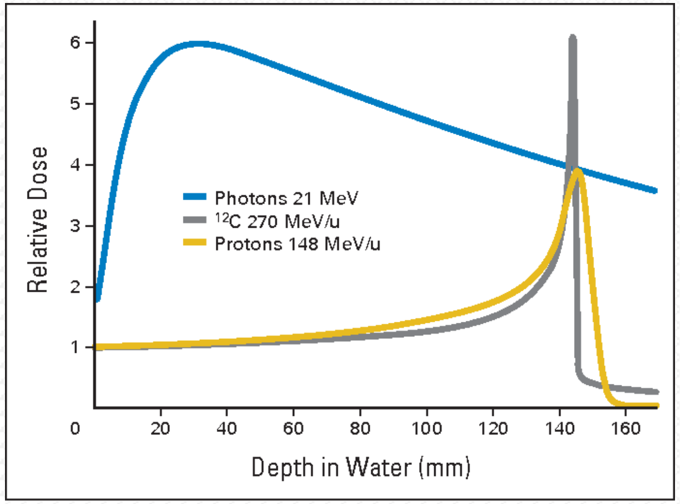
- Study of ion beam effects in model cell-free systems and media, as well as on 2D and 3D cell cultures. Analysis of the influence of ion beams on the functioning, metabolic activity, differentiation and DNA repair system in stem cells of the whole organism.

- Studies for improvement of treatment planning in ion therapy sessions.



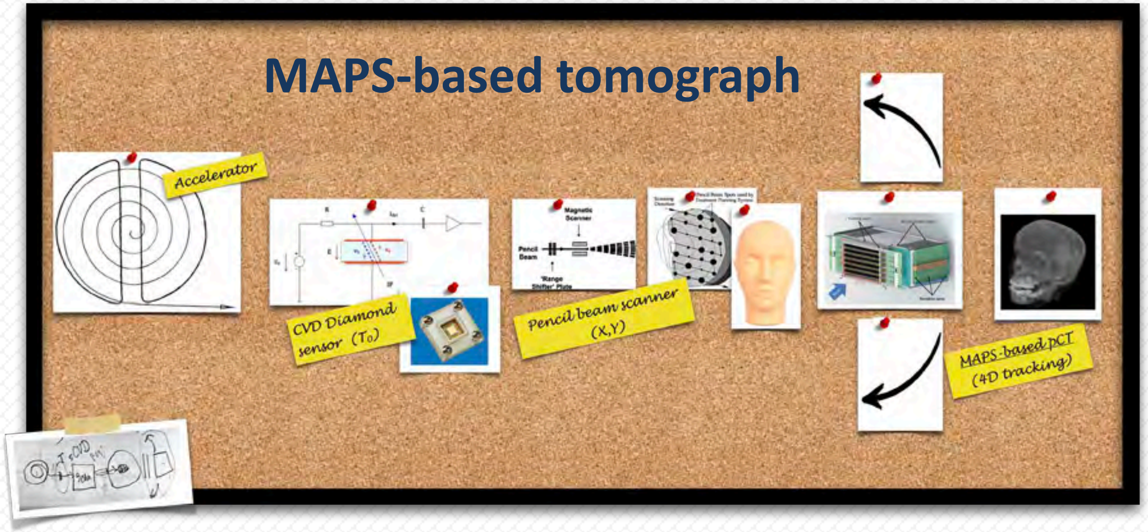
Jiade J. Lu et al. IAEA Scientific Forum, 2017



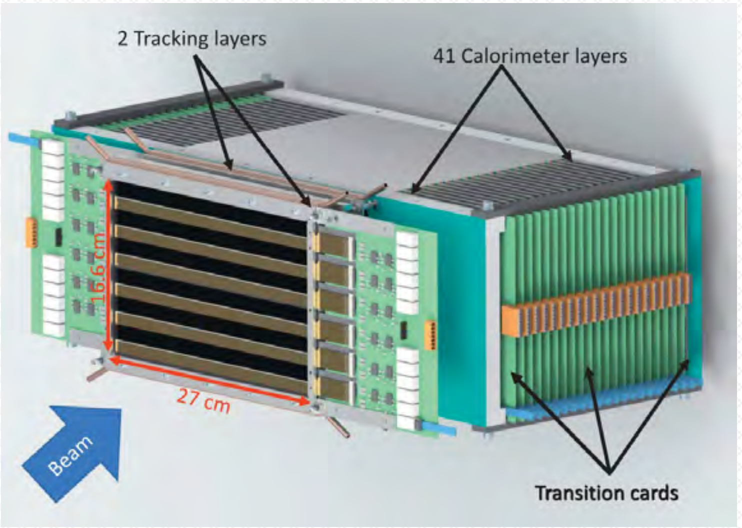


NICA DETECTOR TECHNOLOGIES FOR MEDICINE

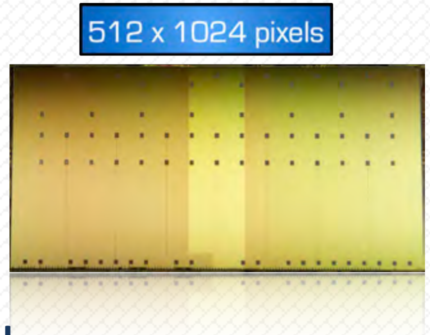
NICA facility is a “zoo” of detectors. Some of them are essential for development of advanced tomography technologies.



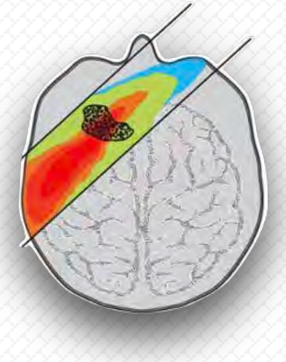
In total we would like to have 48 planes with 9 x 18 MAPS chips each for a total of about 7300 chips



MAPS = Monolithic Active Pixel Sensor



Photon

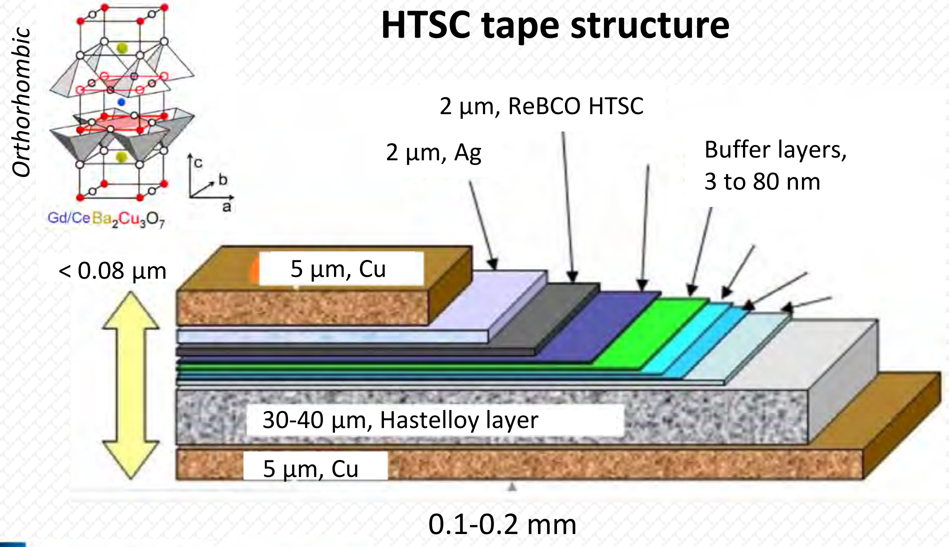


Proton

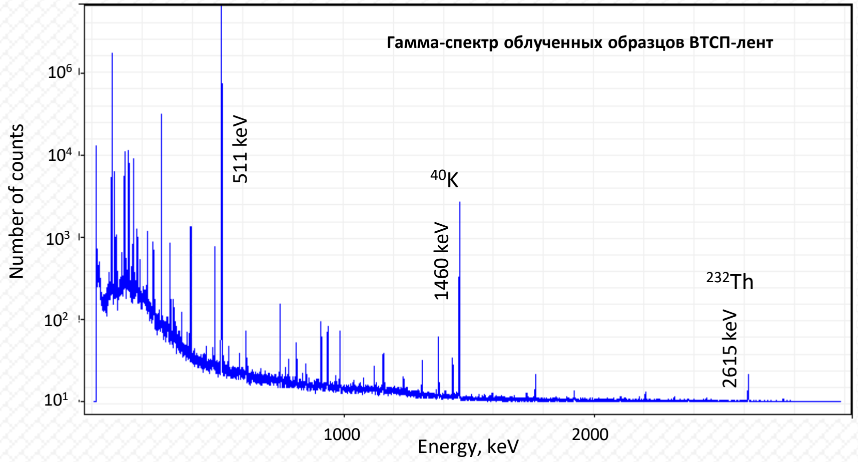
Improving the treatment planning for proton therapy:
By ensuring diagnosis-therapy particle consistency the uncertainty ranges goes down to 0.3 - 1% versus ~7.4% with tomography practices used in present-day medicine

III. Materials Science working package:
Radiation modification of high-temperature superconducting tapes

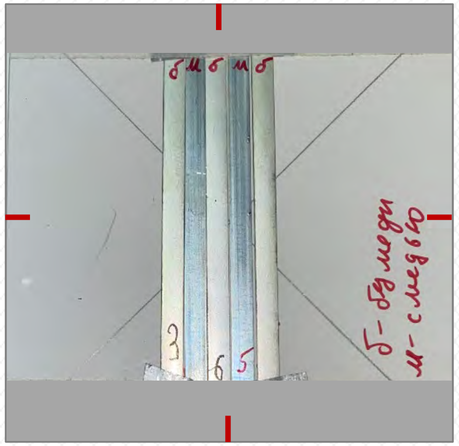
- Development of methods for increasing the critical current of high-temperature superconductors (HTSC) by means of radiation modification (induction of pinning centers in the bulk of the superconductor).
- Comparative analysis of the critical current values upon irradiation of HTSC tapes with $^{124}Xe^{54+}$ ions of 3.8 GeV/nucleon and protons of 660 MeV.
- Estimation of the stability of the effect of increasing the critical current in an irradiated superconductor.
- Development of equipment prototypes based on radiation-modified HTSC tapes and their testing.

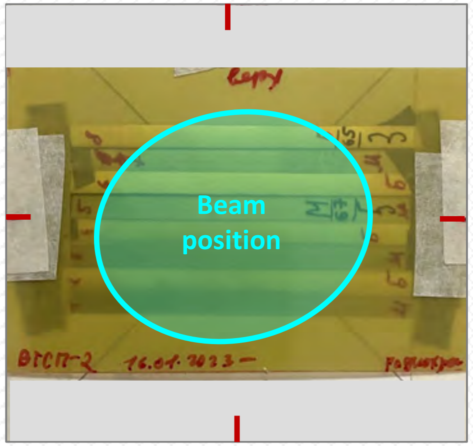


Methods for measuring current-voltage characteristics, Hall coefficient, magnetoresistance, thermo-EMF coefficient, thermal conductivity coefficient, magnetic moment in the temperature range of 1.7–300 K and magnetic fields up to 8 T.



Irradiation of vertically and horizontally arranged HTSC tapes with and without copper content



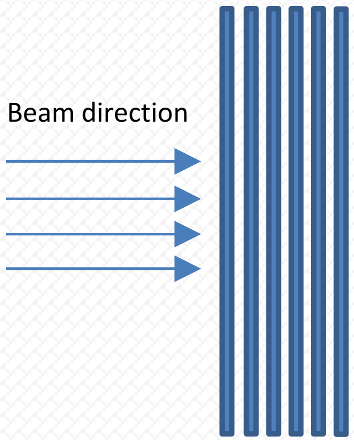


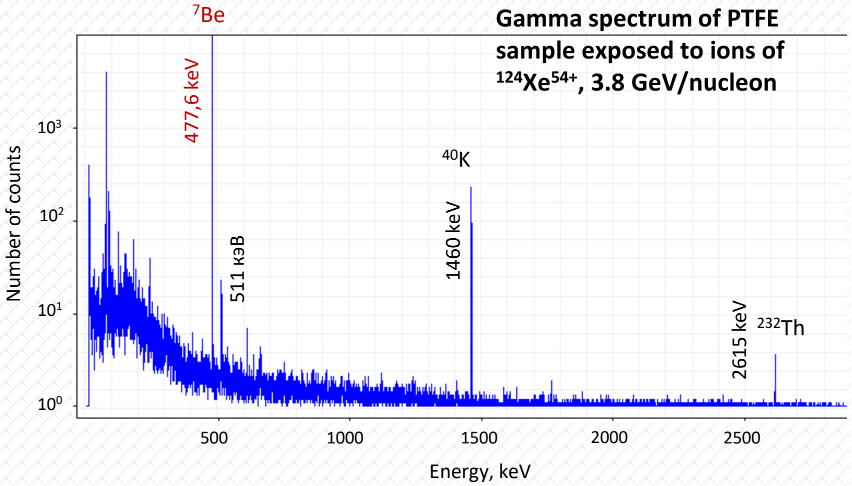
TSC tapes manufactured by "SuperOx" LLC

Radiation modification of polytetrafluoroethylene (PTFE), polyethylene terephthalate (PET), polyethylene (PE) and polyimide (PI) films

- Study of the processes of amorphization and recrystallization of polymers and nanocomposite materials.
- Investigation of regularities of radiation-chemical damages in PTFE, PET, PE and PI films.
- Establishment of regularities in radiolysis of condensed matter under the exposure to ion beams with energies of several GeV/nucleon.
- Development of ion-track technologies with "thick" targets and multilayer materials.

Multilayer film packs for exposure



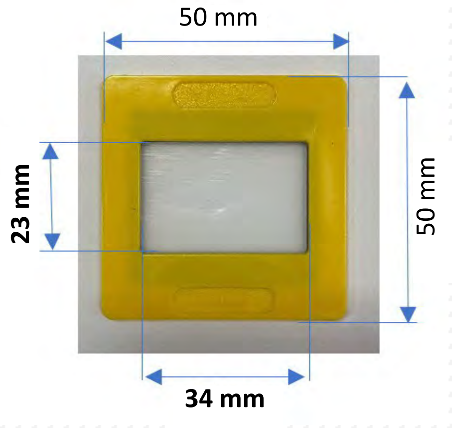


PTFE, PET, PE and PI films of 12, 20, 40, 50, 80 µm thick

Research methods: scanning and transmission electron microscopy, X-ray phase analysis, X-ray photoelectron spectroscopy and X-ray energy-dispersive elemental analysis, atomic force microscopy and low-temperature nitrogen sorption, wettability with respect to water and heptane, optical and infrared spectroscopy, infrared spectroscopy of frustrated total internal reflection, diffuse spectroscopy and specular reflection, laser Doppler strainmetry.

SOCHI FACILITY: TEST EXPERIMENT WITH IRRADIATION OF TRM-PTFE FILMS

TRM-PTFE films of 20 and 100 μm



Formula: $(C_2F4)_n$

Density TRM-PTFE: 2.20 g/cm^3

Irradiation area at the film: 23 x 34 mm

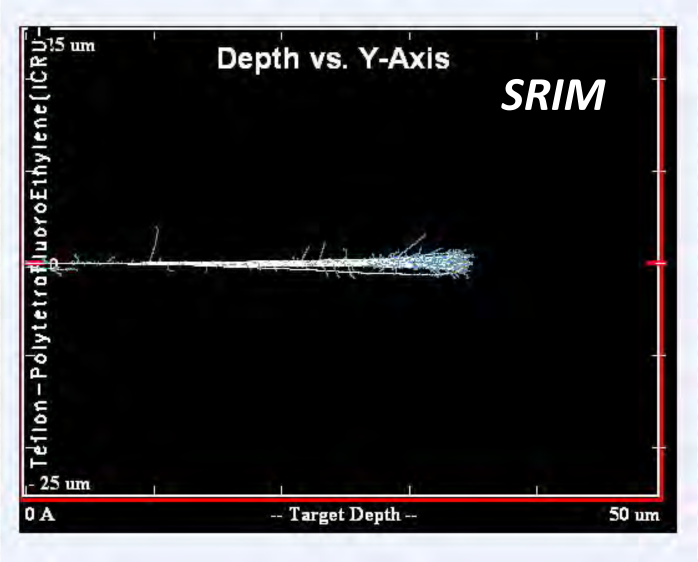
EXPOSURE TO 3,2 MEV/NUCLEON $^{124}Xe^{54+}$ IONS

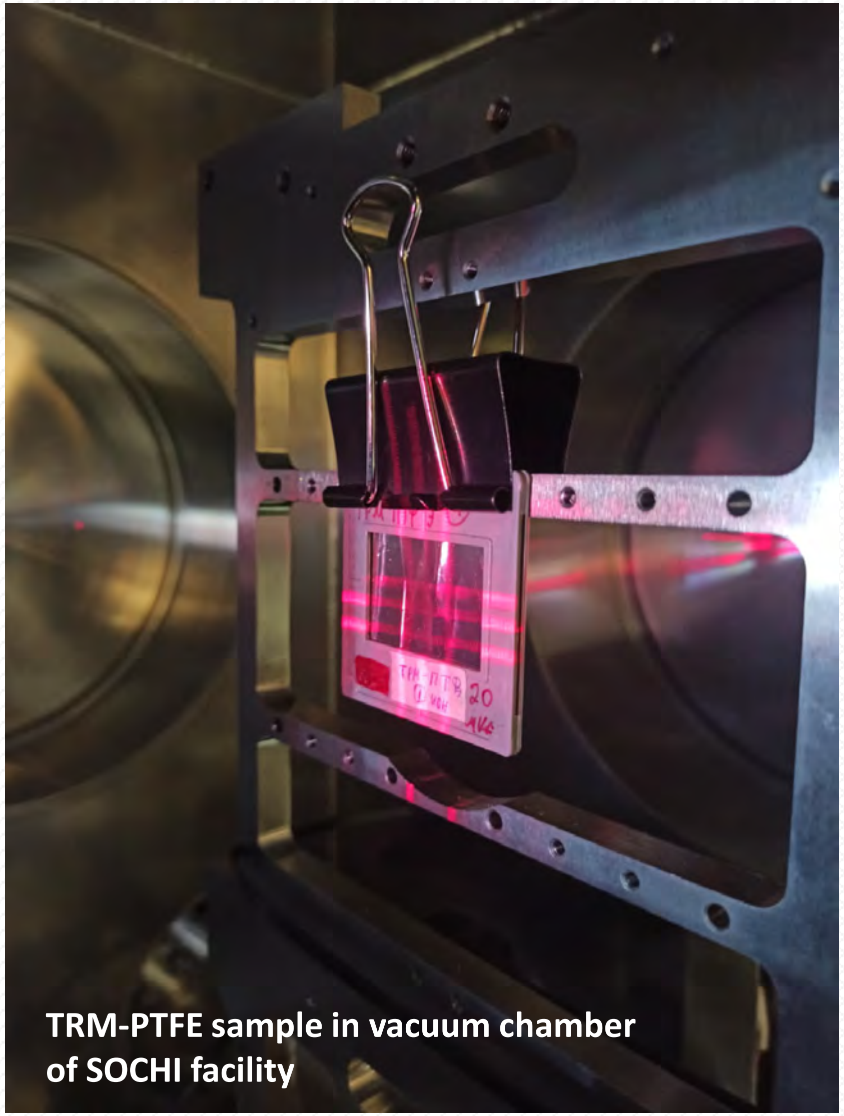
Irradiation in a vacuum chamber

Sample # 1 (20 μm): Φ = 1.08 x 10^6 particles/cm^2

Sample # 2 (20 μm): Φ = 1.12 x 10^5 particles/cm^2

Sample # 3 (100 μm): Φ = 1.08 x 10^6 particles/cm^2



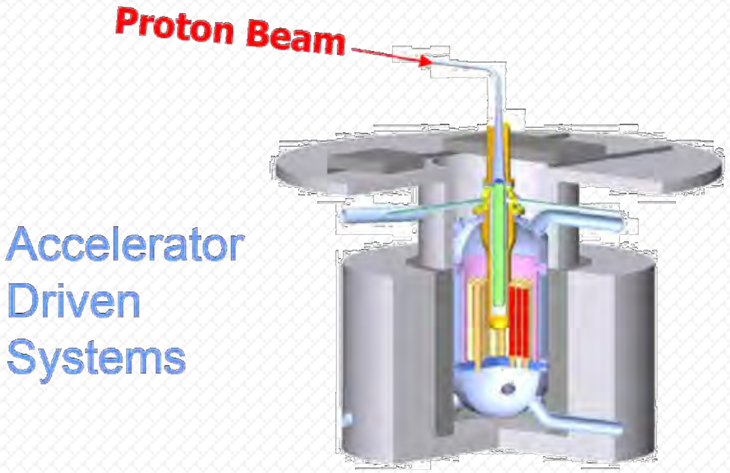


TRM-PTFE sample in vacuum chamber of SOCHI facility

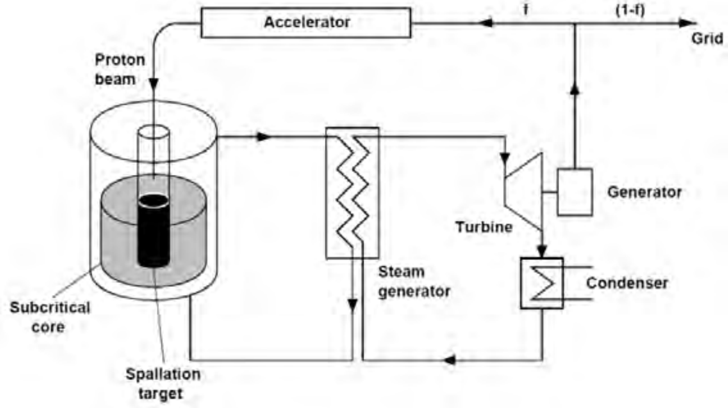
IV. Applied nuclear technology work package

Accelerator Driven Systems (ADS) are the nuclear systems based on interaction of particle beams extracted from the accelerator with deeply subcritical quasy-infinite active zones consisting of the depleted (natural) uranium, thorium and spent nuclear fuel.

In previous years, the conditions which maximize the efficiency of ADSR were investigated. The optimal value of criticality coefficient of the core k_{eff} is in the range 0.985 - 0.988. It was suggested that the best choice for the converter is Be, especially for ion beams at low energy.

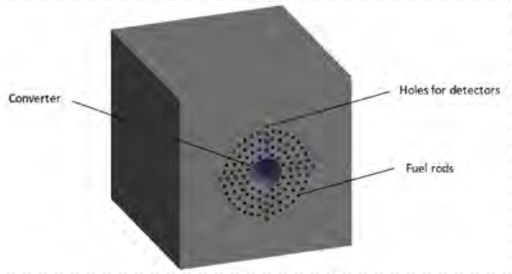


The maximum energy gain of protons is obtained at 1.5 GeV when they are accelerated in a LINAC, and at lower energy (0.75-1 GeV) when a cyclotron is used. In both situations ion beams starting with ^{4}He realize higher energy gain than protons. When particles are accelerated in a LINAC, at low accelerator length a beam of ^{7}Li with energy 0.25 AGeV represents the best option.



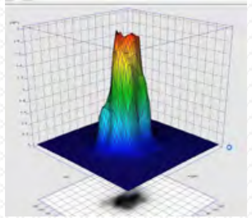
Within the next years the ADSR project will be concentrated on:

- **Research activities, involving simulation study, on an optimal design of the target;**
- **Verification of a principally new concept of a system based on the use of ion beams instead of protons;**
- **Implementation of the first stage of experimental program focused on measurement of the neutron yields with different converter combinations.**

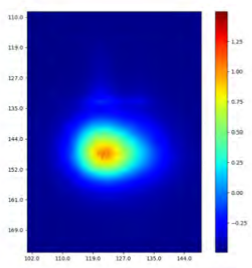


V. Routine analysis: Dosimetry and activation measurements after irradiation

OCTAVIUS Detector 1500 XDR

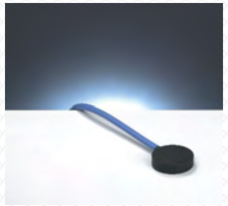


3D-map of exposure

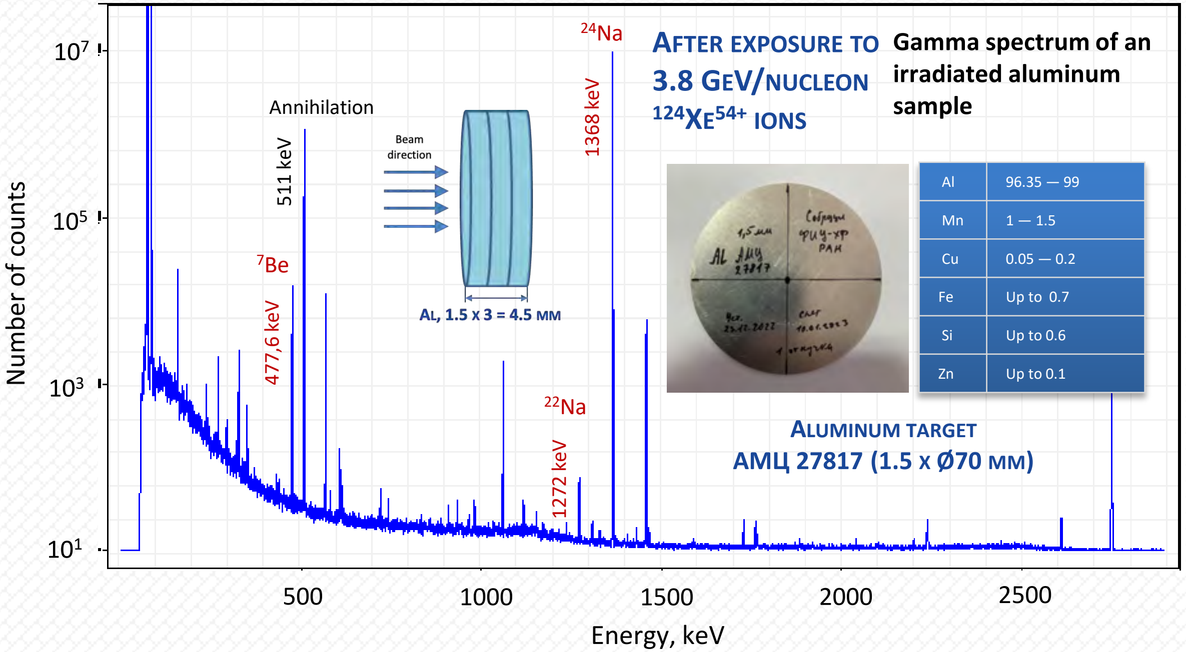


Beam profile (OCTAVIUS Detector 1500 XDR)

Ion chamber TM30010-1



Ion chamber TM34001 Roos



DKS-AT5350/1

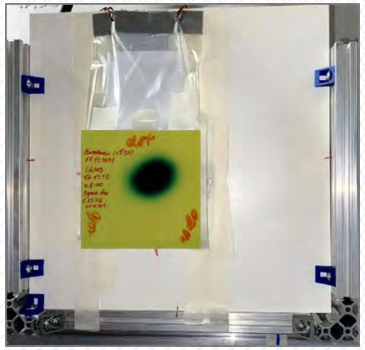
Gamma dosimeter DBG-S11D

Spectrometer of gamma radiation SEG-1KP-IFTP (detection unit BDEG-OGK-3K)

Status of the ARIADNA Research Programme @ NICA

ARIADNA – Applied Research Infrastructure for Advanced Developments at NICA fAcility

First High-energy Beam for Applied Research @ NICA

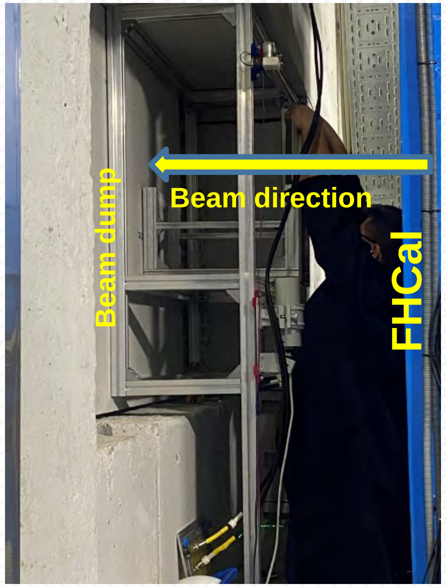


$^{124}Xe^{54+}$

3.8 GeV/nucleon

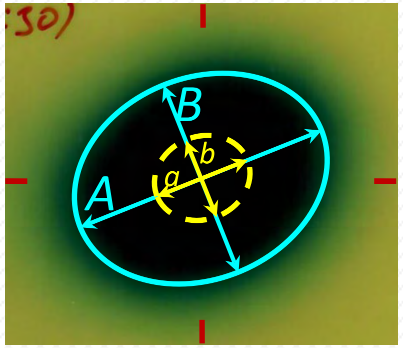
First run: 11 December 2022 – 30 January 2023

Beam trace at the EBT3 radiochromic film



Installation of dosimetry equipment and samples to ARIADNA target station in BM@N zone

The Research Programme is STARTED



Beam profile

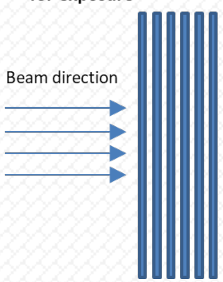
A = 34.2 mm
B = 29.3 mm

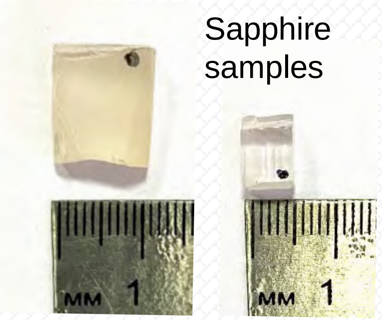
The most uniform area:
a = 12.0 mm
b = 9.0 mm

Development of ARIADNA Collaborations

- Composition of collaboration: 21 institution;
- Total number of participants (as of 6 September 2023): 157.

Radiation Materials Science

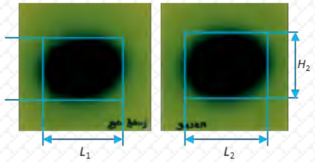




Sapphire samples

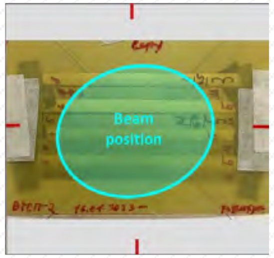
Composite Materials

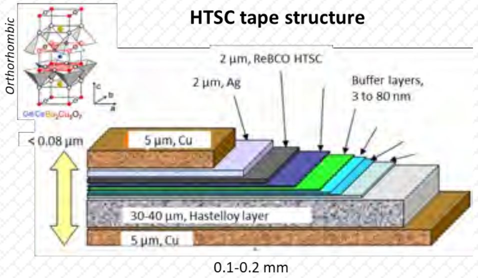
Composite material at ISS



New composite material for ROSS

Radiation Modifications In High-temperature Superconductors





Ways of getting involved in ARIADNA

- As a **member of ARIADNA collaboration:** get in touch with us and we will provided instructions on signing an MoU to become a member of the collaboration.
- As a **user:** just prepare and submit you proposal for consideration.
- As an **ARIADNA partner:** let us know how you think you/your research team or company can contribute to ARIADNA and we can prepare a relevant application to be discussed with NICA management.

Thank you for your attention

Contact information:

Oleg Belov

Veksler and Baldin Laboratory of High Energy Physics,

Joint Institute for Nuclear Research

E-mail: oleg.belov@jinr.int