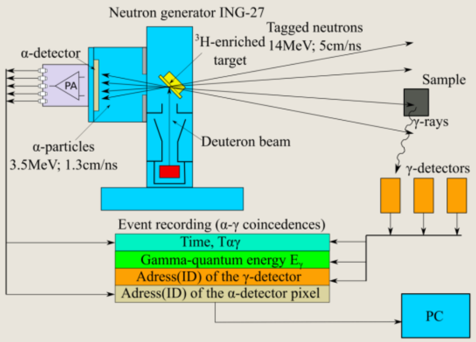
Condensed Matter and Nuclear Physics Research at Frank Laboratory of Neutron Physics

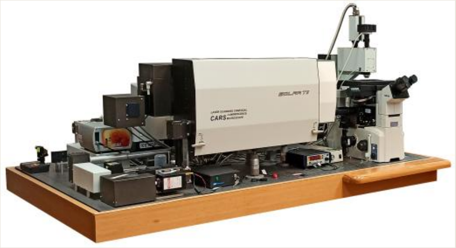
Yuri Kopatch

Frank Laboratory of Neutron Physics
Joint Institute for Nuclear Research
Dubna

FLNP – Frank Laboratory of Neutron Physics

Ilya Mikhailovich FRANK
(1908-1990)





Two scientific fields:

Condensed matter physics;

•Nuclear physics with neutrons;

Basic facility:

–IBR-2 – pulsed research reactor;

– Other facilities:

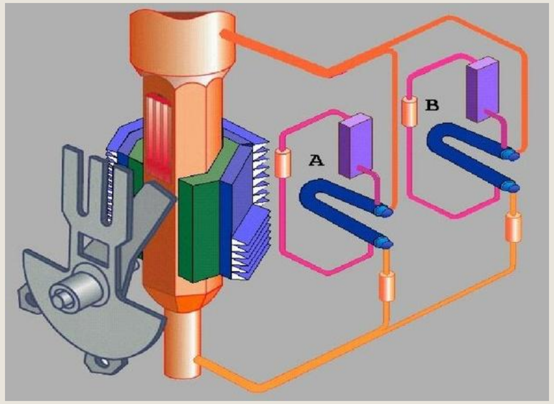
–IREN – resonance neutron source;

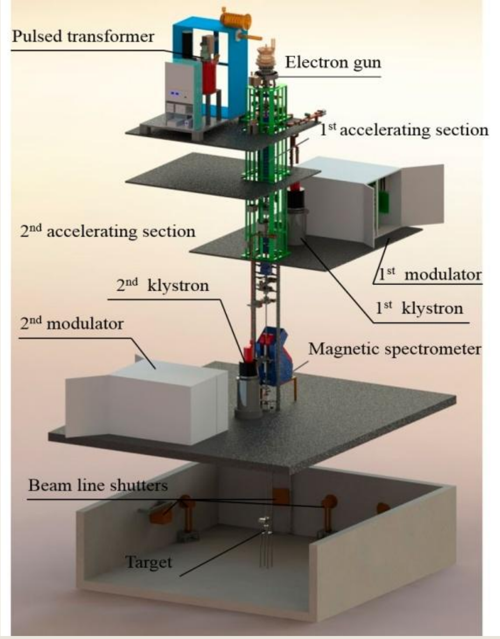
–EG-5 Van de Graaf accelerator;

–TANGRA (neutron generator ING-27)

–CARS – Raman microscope;

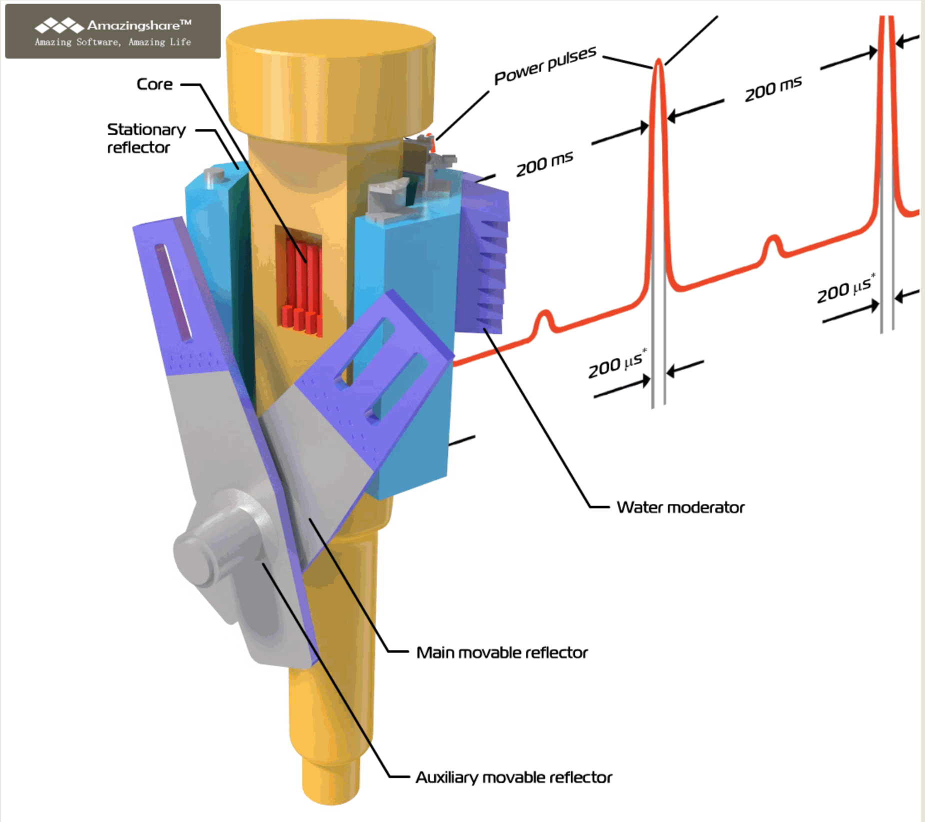
About 250 papers published annually





High Flux Pulsed Reactor IBR

- **IBR-2 operates successfully from 1984**
- **modernization of all components in 2006-2010**
- **IBR-2 service life until 2040 (additional refueling)**



Operating time: 2500 hours/year

Average power, MW	**2**
Fuel	PuO_2
Number of fuel assemblies	69
Maximum burnup, %	9
Pulse repetiton rate, Hz	5
Pulse half-width, μs: fast neutrons thermal neutrons	 200* 340
Rotation rate, rev/min • Main reflector • Auxiliary reflector	 600 300
MMR and AMR material	Nickel + steel
MR service life, hours	55 000
Background, %	7
Termal neutron flux density from the surface of the moderator • Time average • Burst maximum	 $\sim 10^{13}$ n/cm^2 s $\sim 10^{16}$ n/cm^2 s

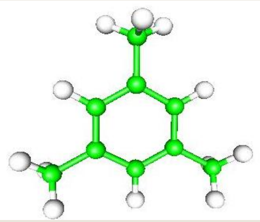
High Flux Pulsed Reactor IBR

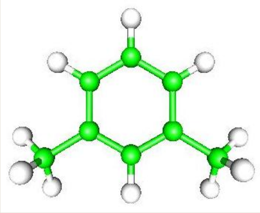
Water Moderators

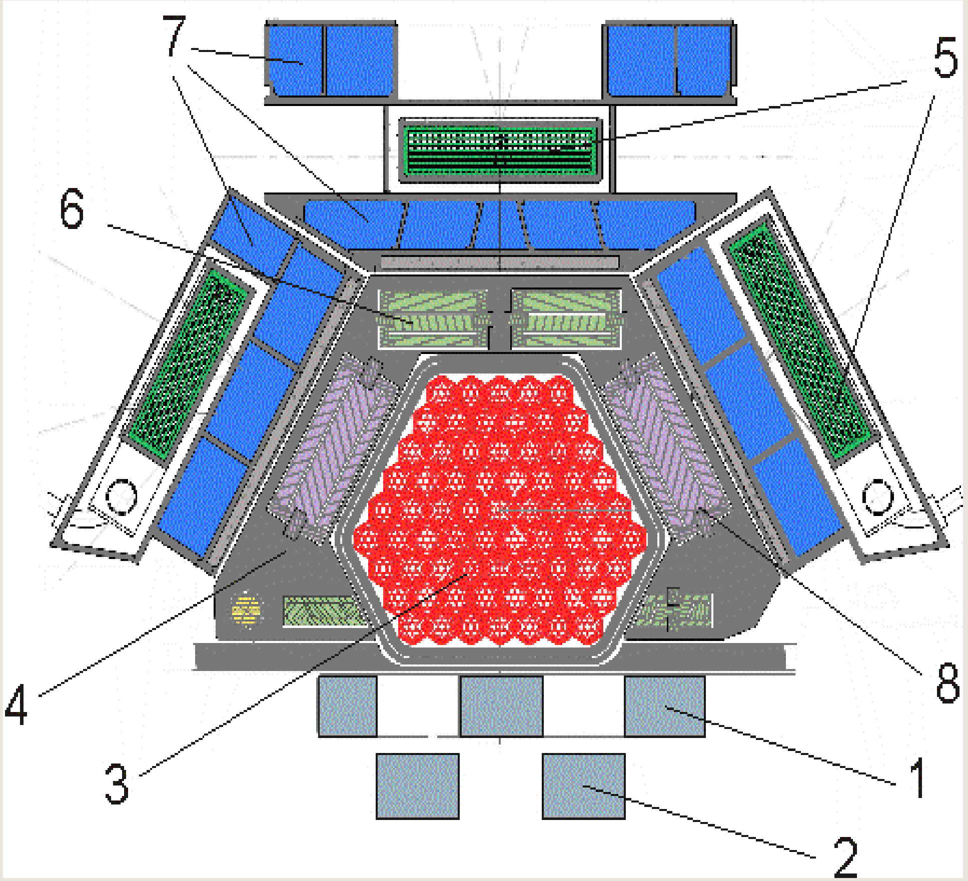
Thermal neutrons
0.025 eV

Cryogenic moderators
– developed by FLNP

Cold neutrons
0 - 0.025 eV

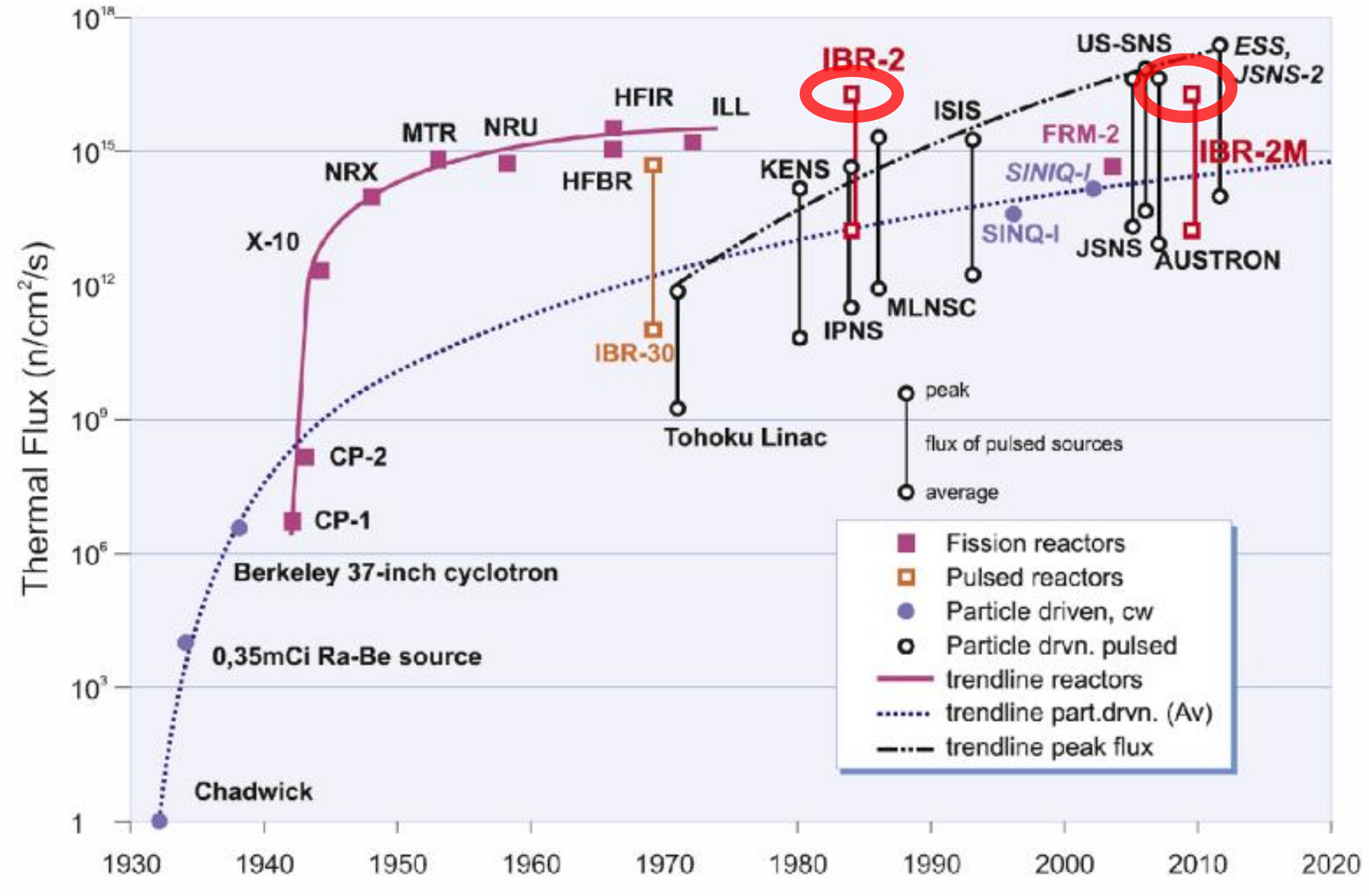




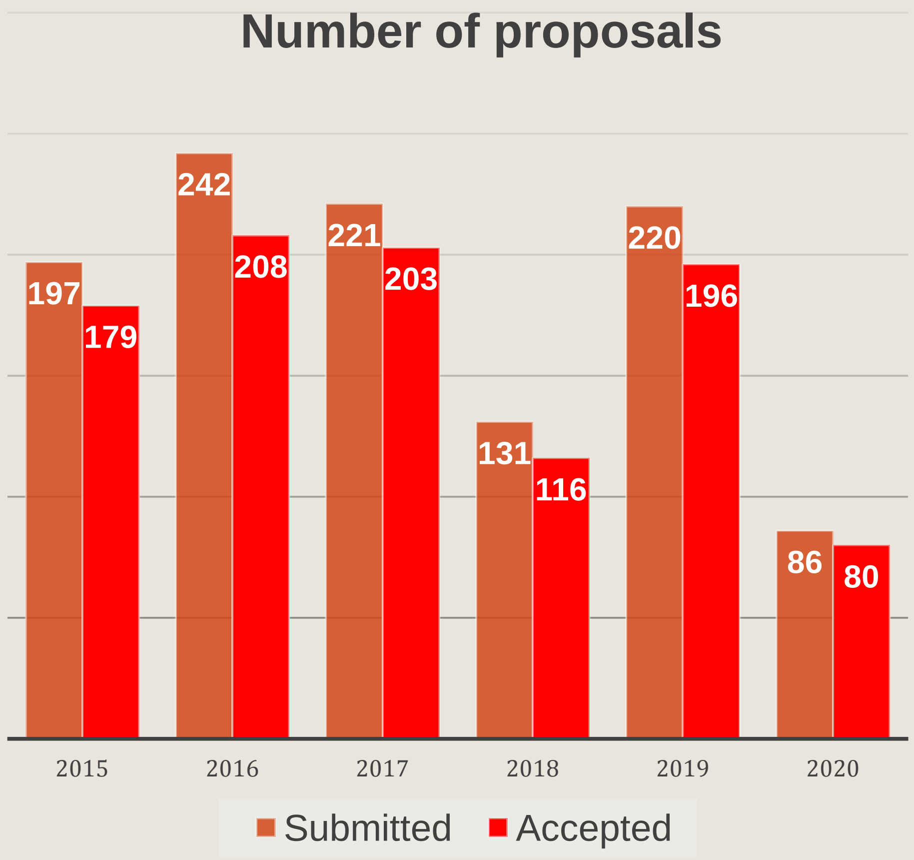


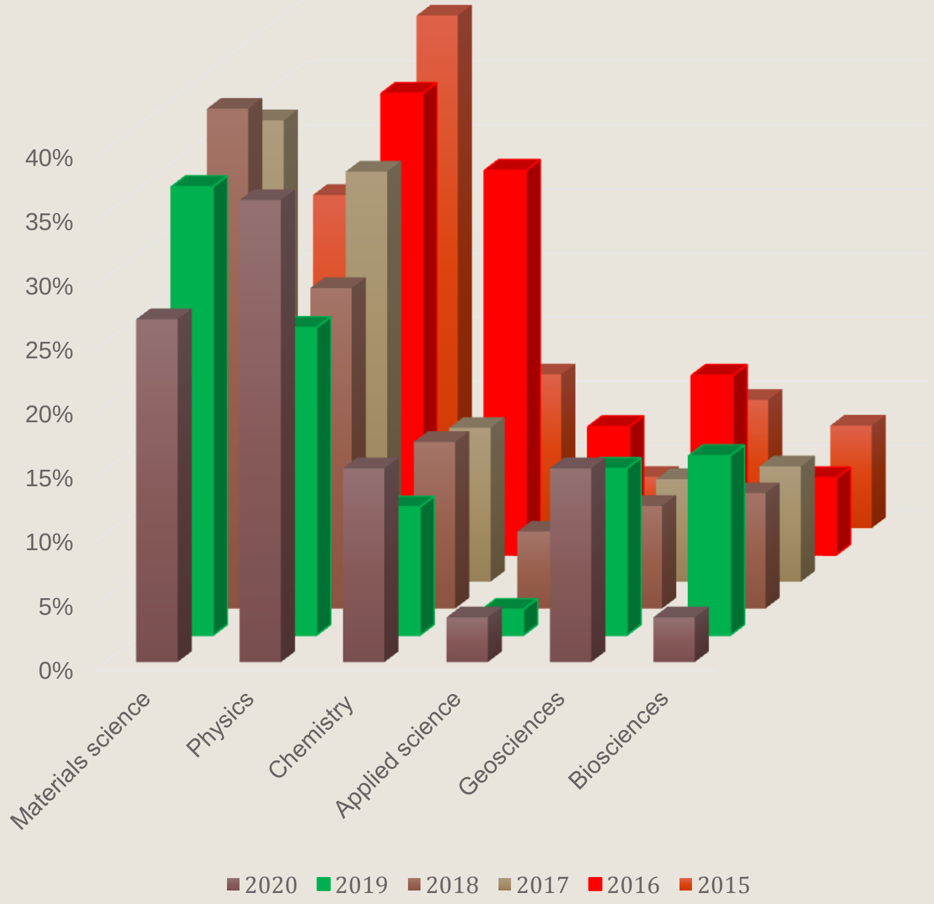
1. Main moveable reflector,
2. Auxillary moveable reflector,
3. Fuel assembly,
4. Stationary reflector,
5. **Cold moderators,**
6. Emergency system,
7. **Water moderators,**
8. Control rods;

Neutron Sources Around the World



User Program at IBR-2

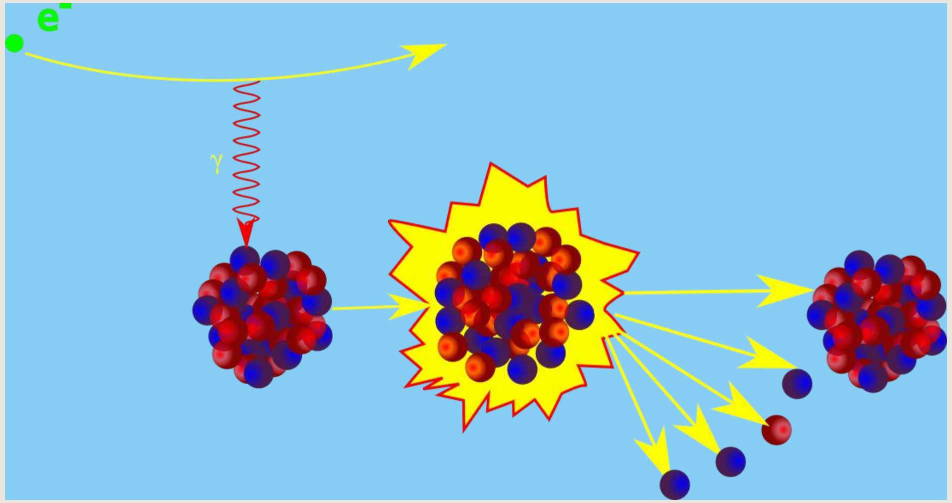


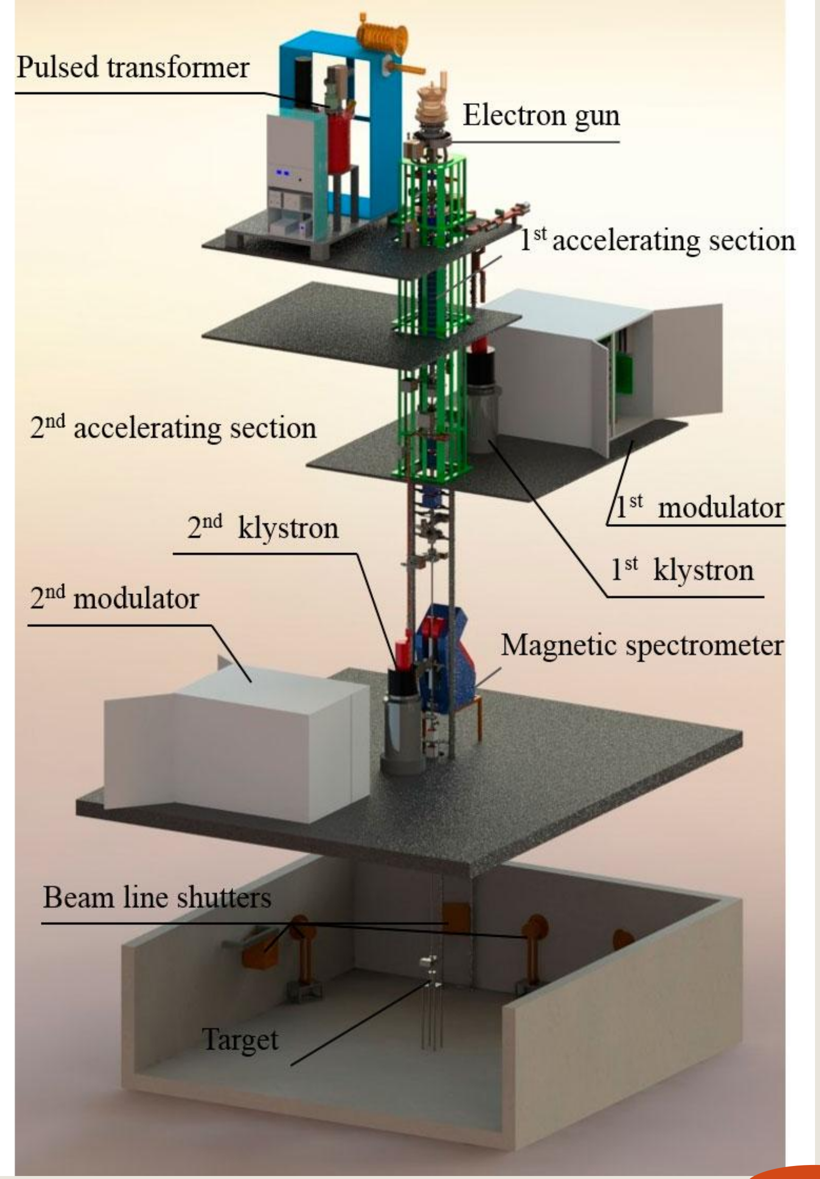


IREN facility

Current IREN parameters:

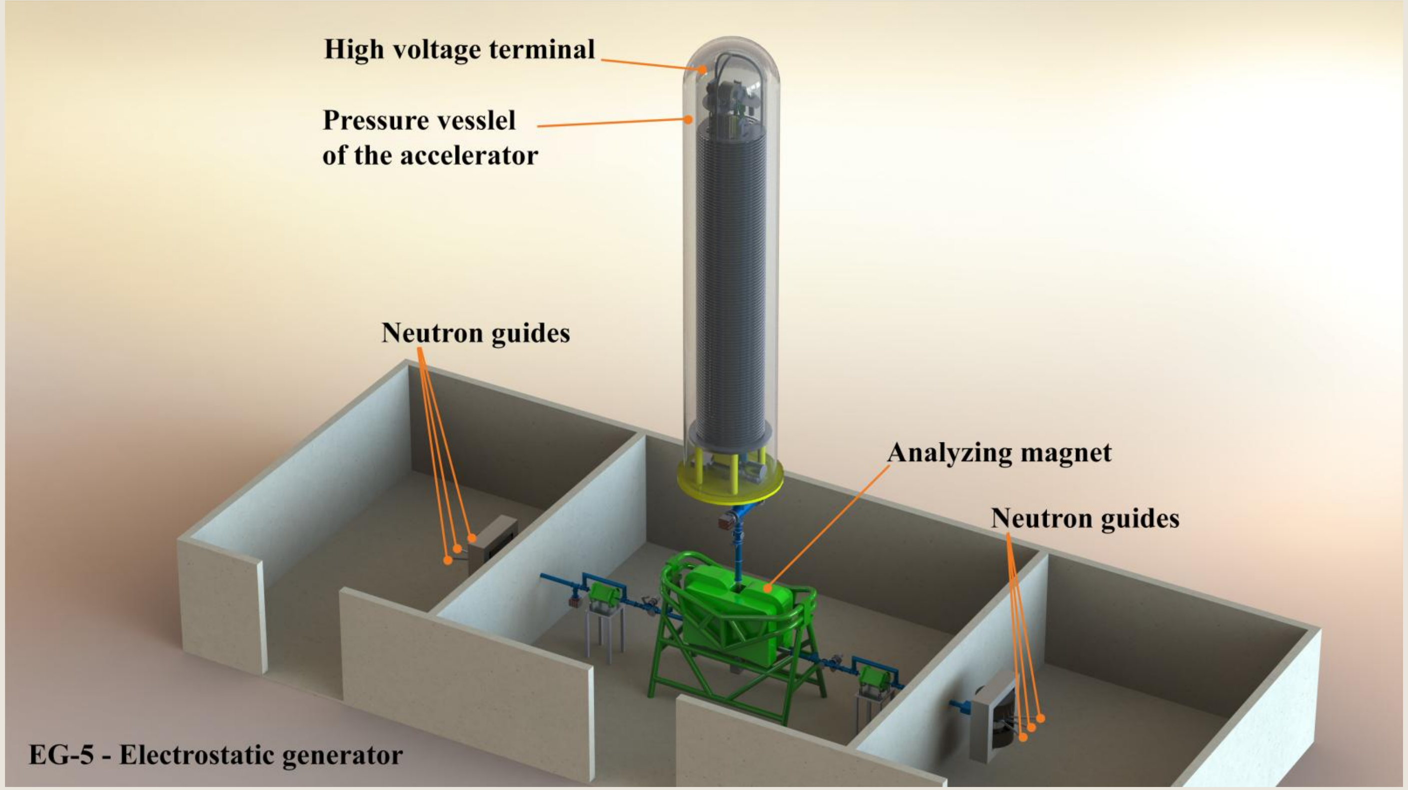
- pulsed electron beam current – 2.0 A
- electron energy – 120 MeV
- pulse width – 100 ns
- repetition rate – 25/50 Hz
- integral neutron yield (3÷5)×10^{11} n/s.
- Neutrons are produced via photonuclear and electronuclear reactions on W target





Operating time: 1200 hours/year

EG-5 facility – Electrostatic Van de Graaff accelerator

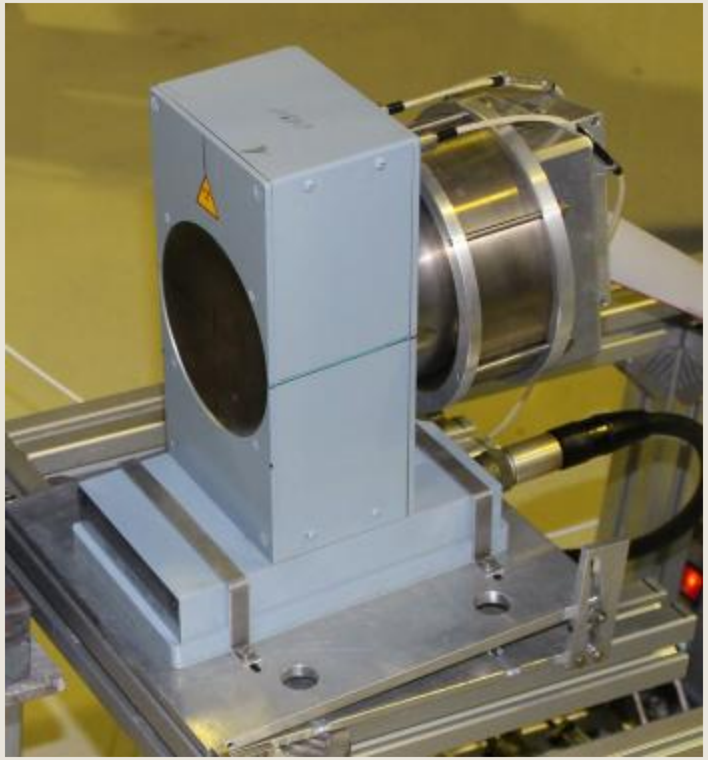


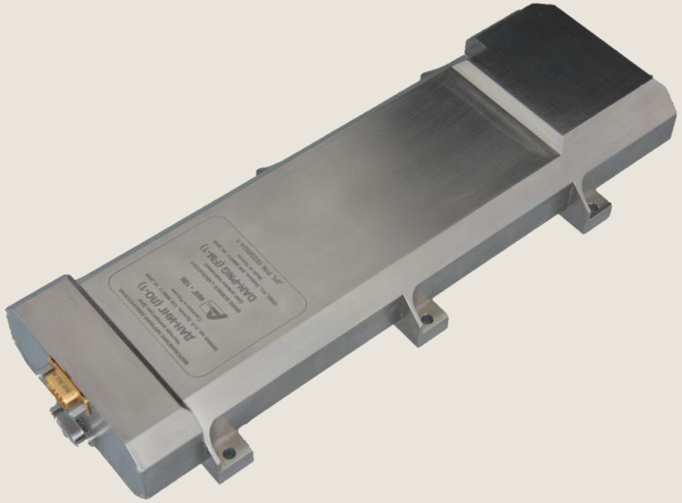
The characteristics of EG-5 Accelerator:
Energy region: 0.9 – 3.5 MeV
Beam intensity for +: 30 μA
Beam intensity for +: 10 μA
Energy spread < 500 eV
Number of beam lines: 6

EG-5 can be used for producing quasi-monoenergetic neutrons in the energy range from 2.5 MeV to 4.1 MeV

Neutron generators

DT, DD neutron generators of 14, 2.5 MeV neutrons with alfa particle PSD
Neutron yield up to 10^8 s^{-1}





Neutron radioisotope sources

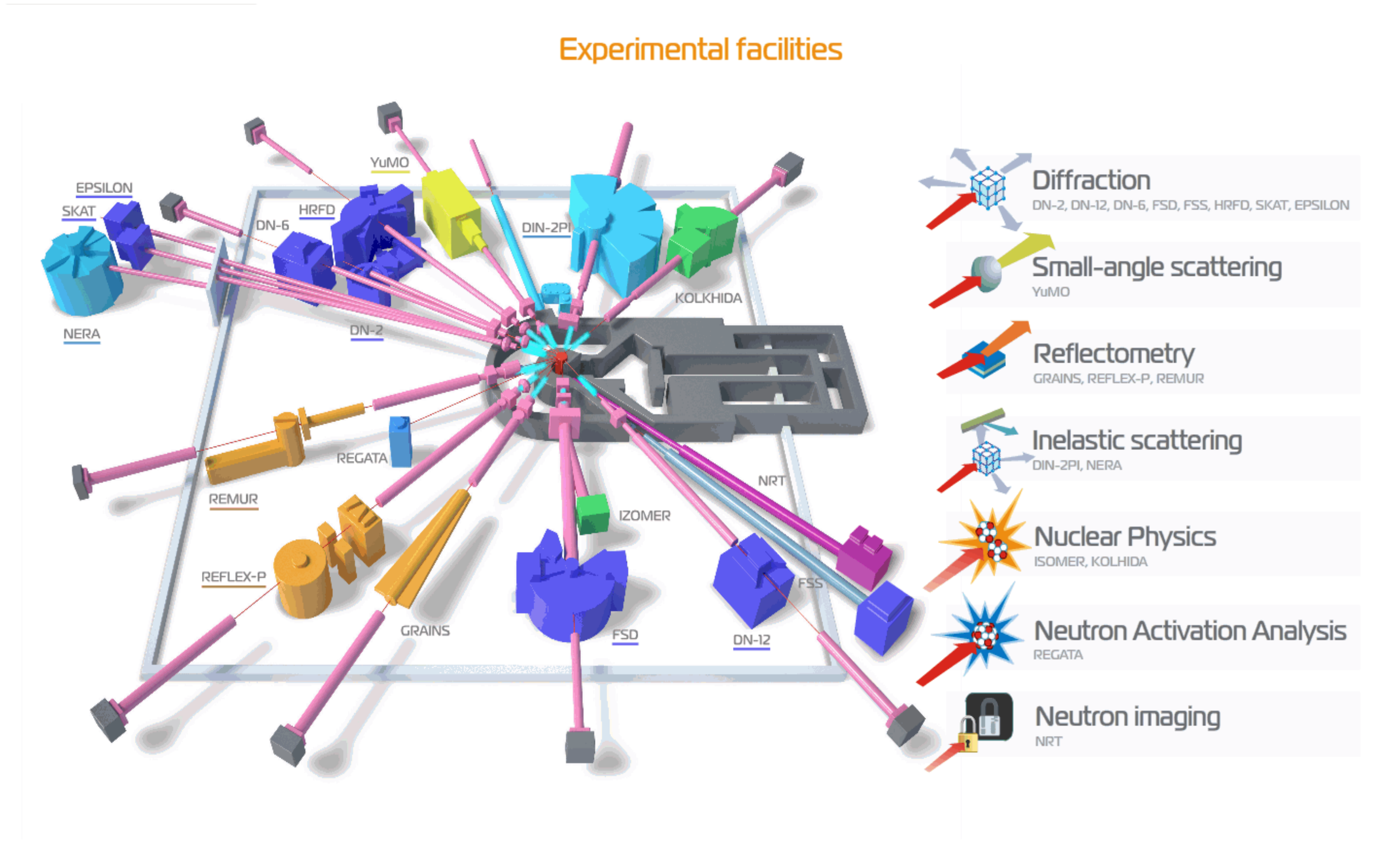
^{252}Cf,
(α,n) ^{241}Am, ^{239}Pu, ^{238}Pu
Intensity $10^5 – 10^7$ s^{-1}

Condensed matter physics at FLNP

Methods

- Diffraction
  - Crystal structure
  - Magnetic structure
  - Phase structure
- Small-angle scattering
  - Structure of nanoparticles in solutions
  - Structure of biomembranes
- Reflectometry
  - Layered structures
  - Surface properties
  - Magnetic structure
- Inelastic scattering
  - Molecular and crystal dynamic
- Neutron imaging

Suite of Spectrometers at IBR-2

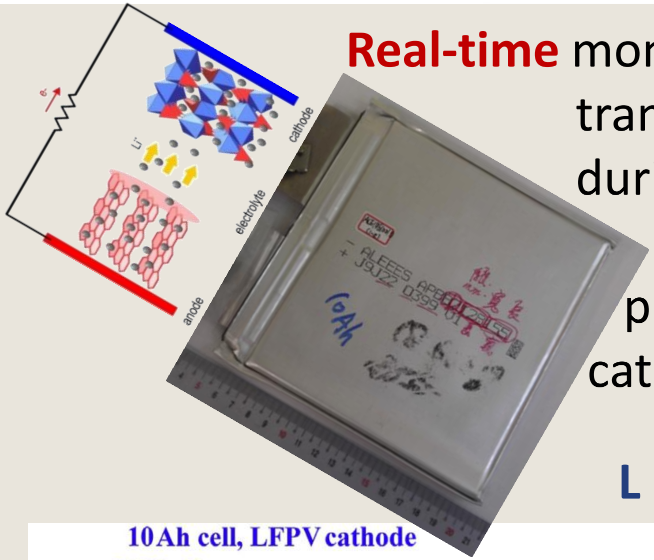


FLNP booklets

https://flnp.jinr.int/images/box-slider/MaterialsScienceBook.pdf

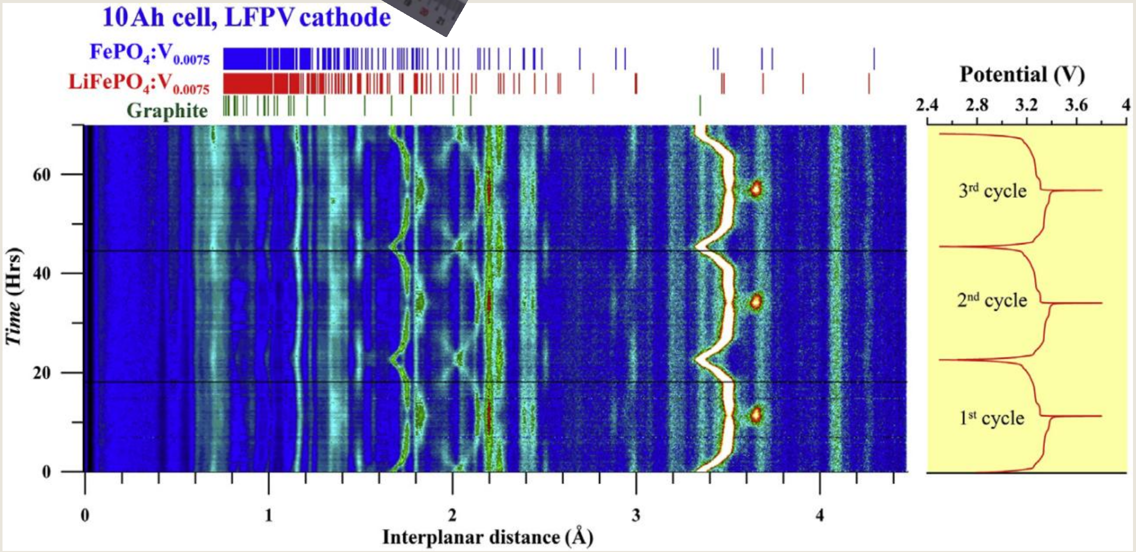
https://flnp.jinr.int/images/LS_FLNP.pdf

Novel Materials for Energy Storage



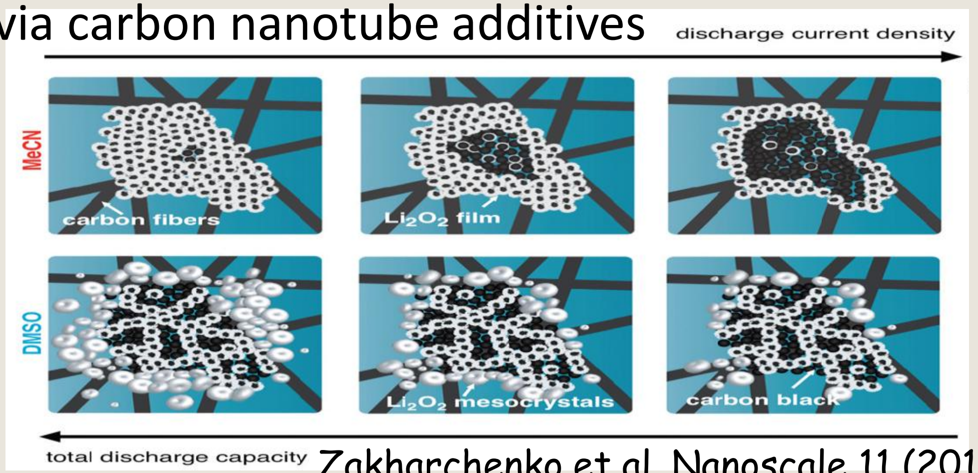
Real-time monitoring of transition processes during charge-discharge revealed improved properties upon doping cathode with vanadium

Lithium-ion technologies



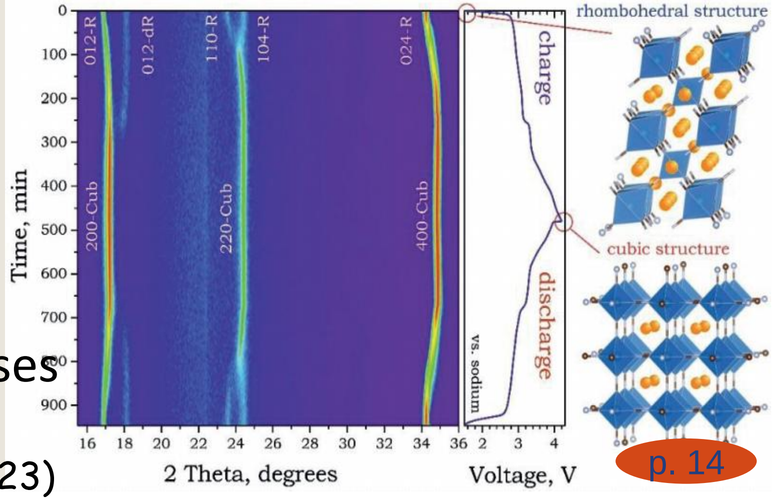
Report by M. Donets at this workshop

Improving the capacity of accumulators by increasing the wettability via liquid electrolyte or via carbon nanotube additives



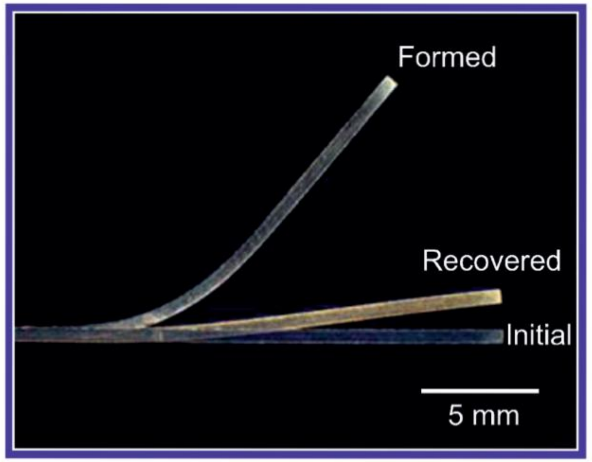
Zakharchenko et al. Nanoscale 11 (2019)
Napolskiy et al. Energy Technology 8(2020)

Alternative current sources based on **sodium ions** may combine with Prussian White cathode changing between cubic and rhombohedral phases

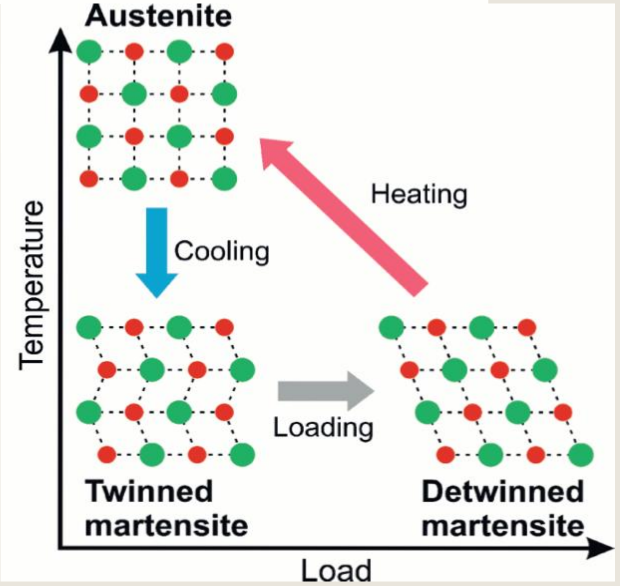


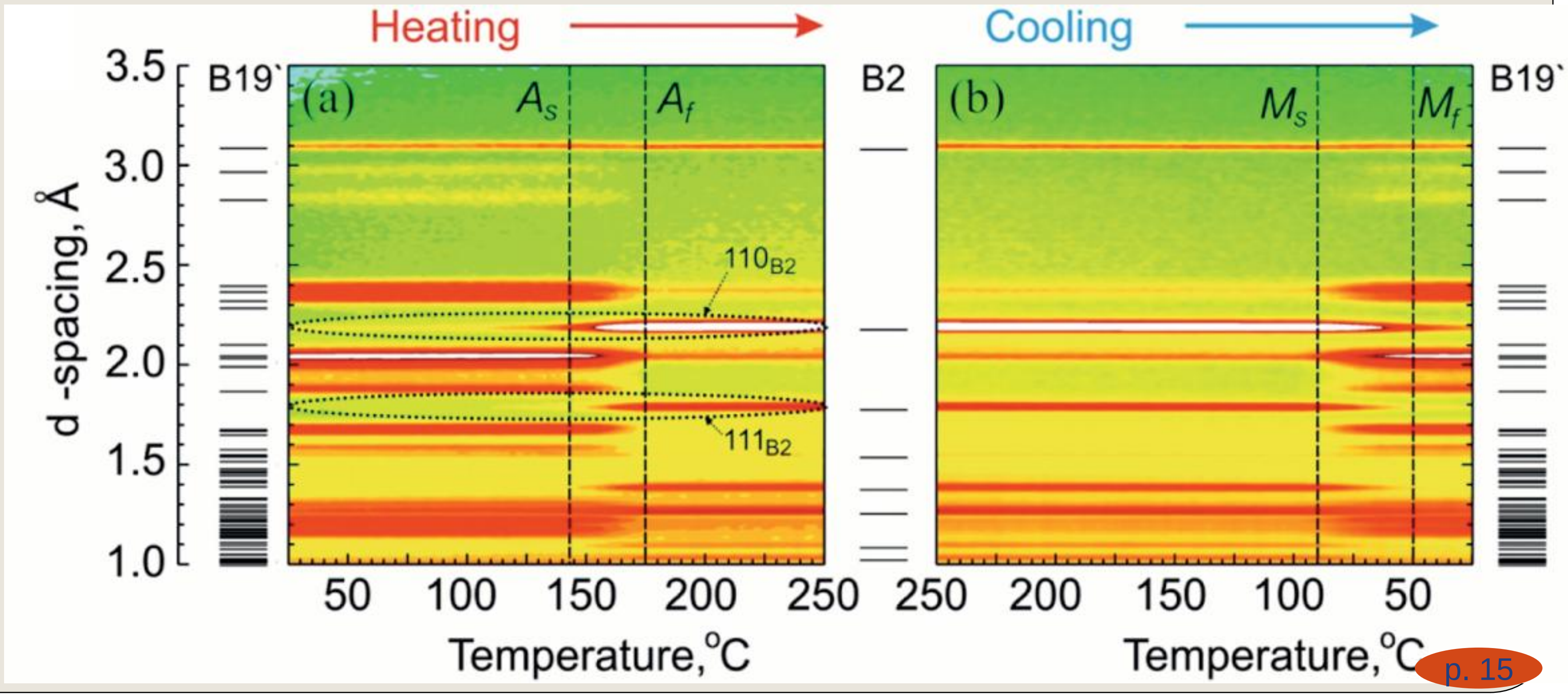
Samoylova et al. JPS (2023)

Alloys with Shape Memory



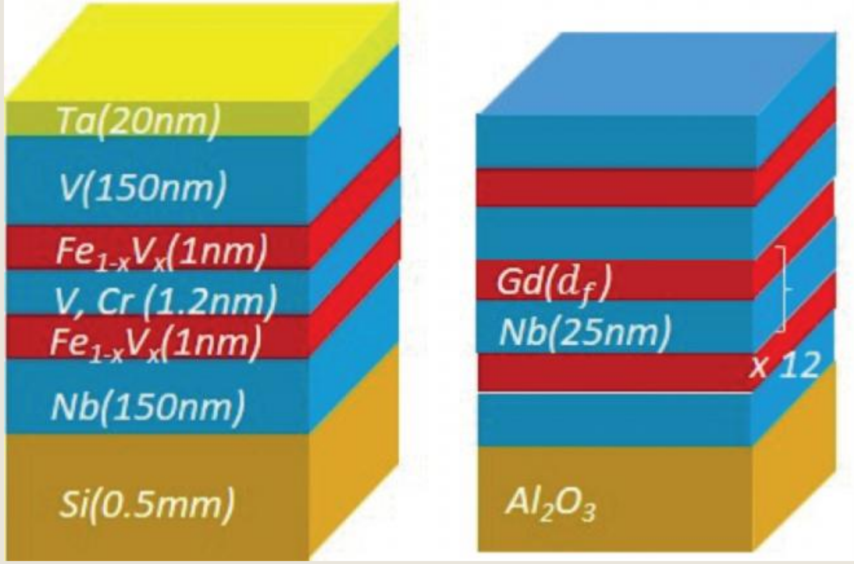
- The **shape memory effect** (SME) is the ability of a material to return to its original shape under external influence (e. g., heating)
- The **crystal structure** of SME alloys ($Ti_{29.7}Ni_{50.3}Hf_{20}$, $Ti_{29.7}Ni_{50.3}Hf_{10}$ Zr_{10}), including during the martensitic transformation were studied at FLNP by **neutron diffraction**
- The negative neutron scattering length of Ti makes ND the **preferred method**





Magnetism and Magnetic Materials

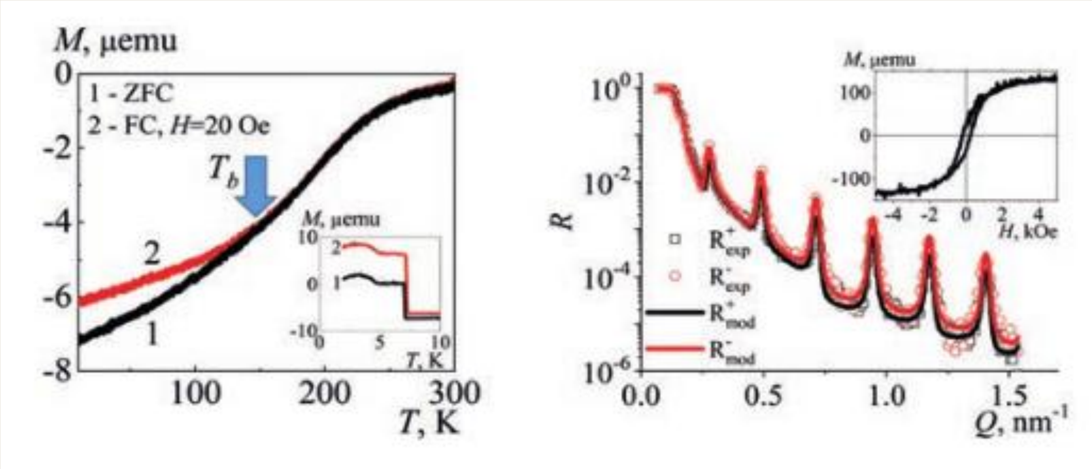
- Superconducting and magnetic properties of the **complex layered heterostructures** are due to superparamagnetic clusters

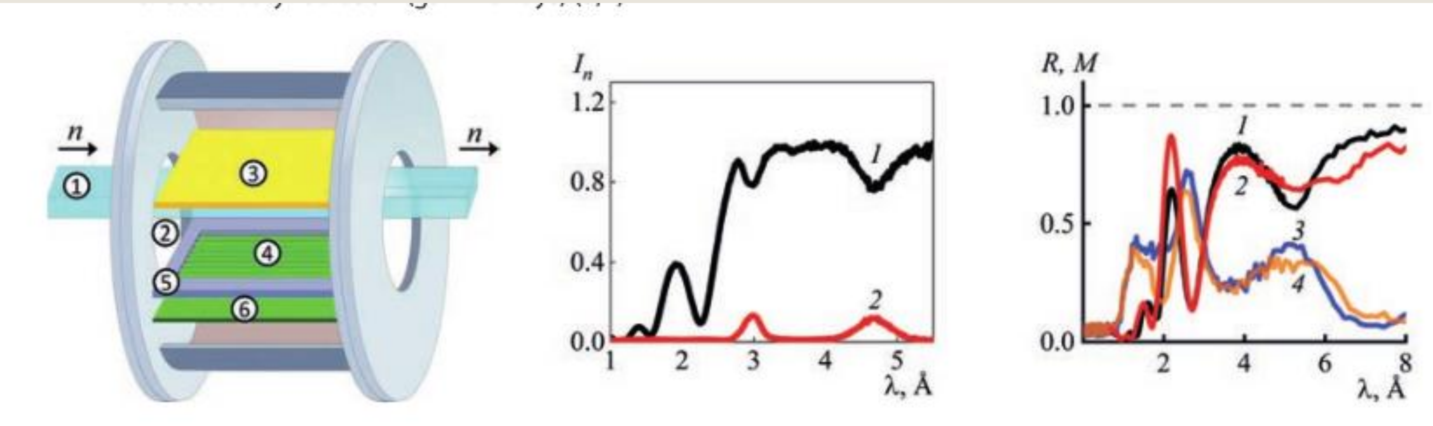


- **Magnetic thin films** with a layered structure open up new opportunities
- Spintronics, magnetic memory devices, quantum computing, superconducting spin valves, polarized electron injectors

V. D. Zhaketov et al. ZhETF 129 (2019)p. 16

Characterization of samples by magnetometry and reflectometry of polarized neutrons for determining magnetization distribution in the layers.



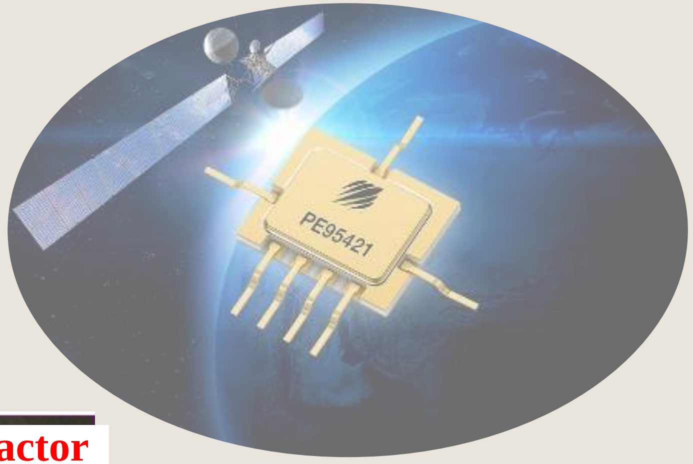


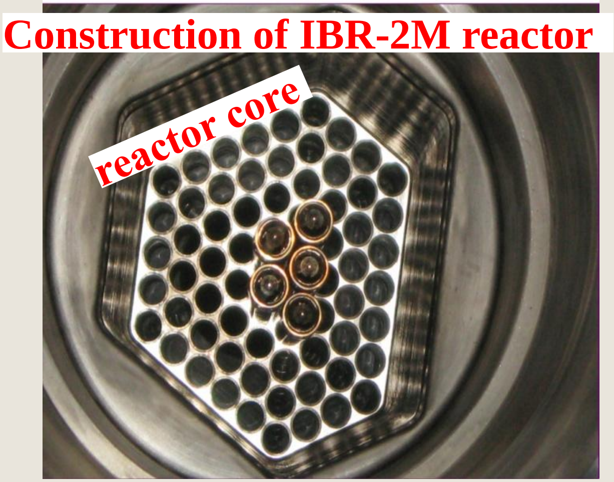
Ionization chamber (1 — neutron beam; 2 — input and output windows; 3 — cathode; 4 — grid; 5 — mesh frame; 6 — anode) for measuring intensity of reflected neutrons (1) and charged particles (2) from Cu(10nm)/V(55nm)/ CoFe(5nm)/6LiF(5nm)/V(15nm)//glass. Neutron reflection coefficient (1,2) and the coefficient of secondary radiation (gamma-rays) (3,4).

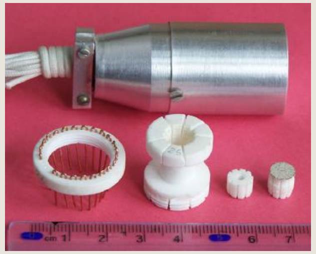
Radiation Resistance Surveillance

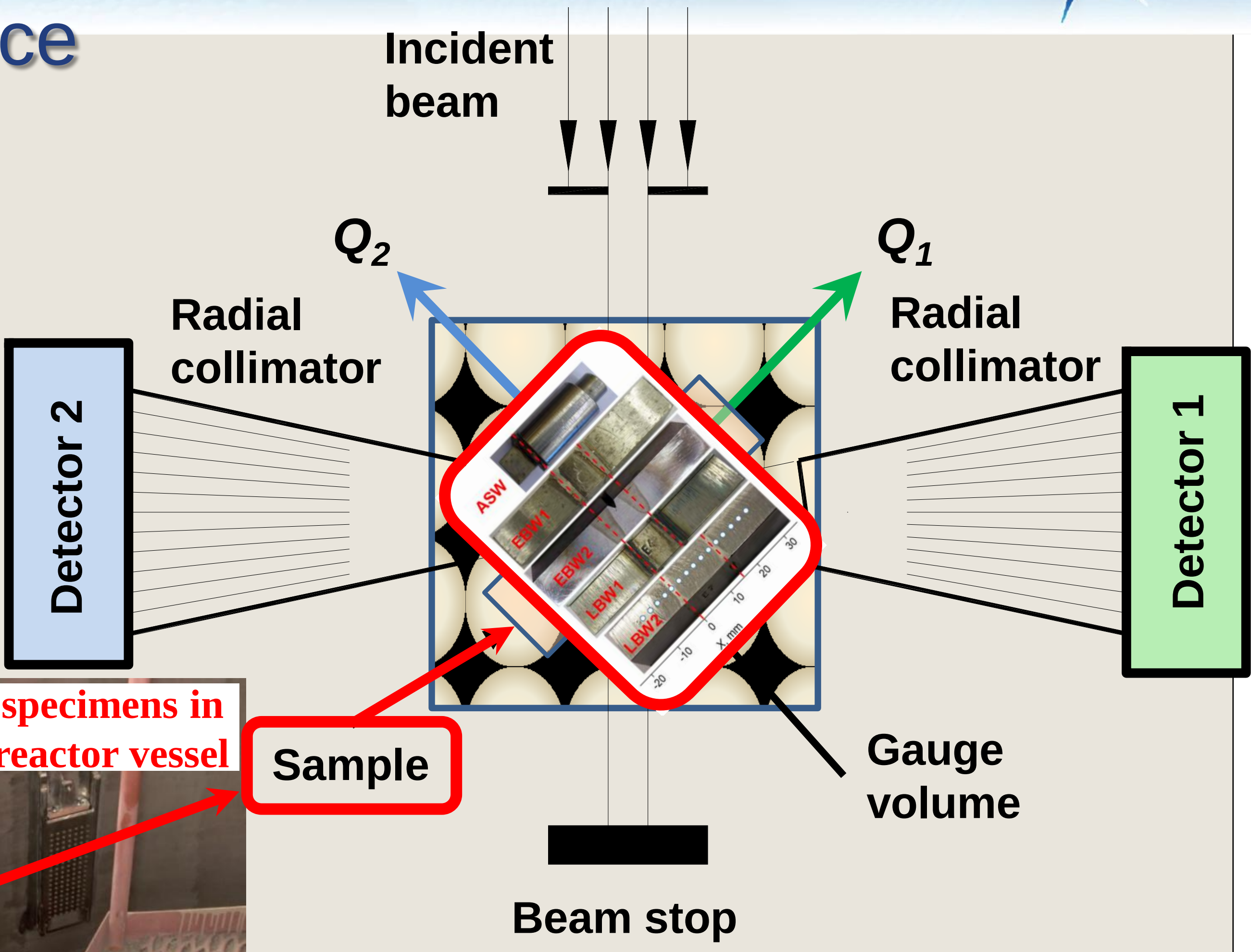
Need for radiation-resistant **materials and electronics**

- Nuclear Reactors
- Accelerators
- Solar Cells
- Space Equipment









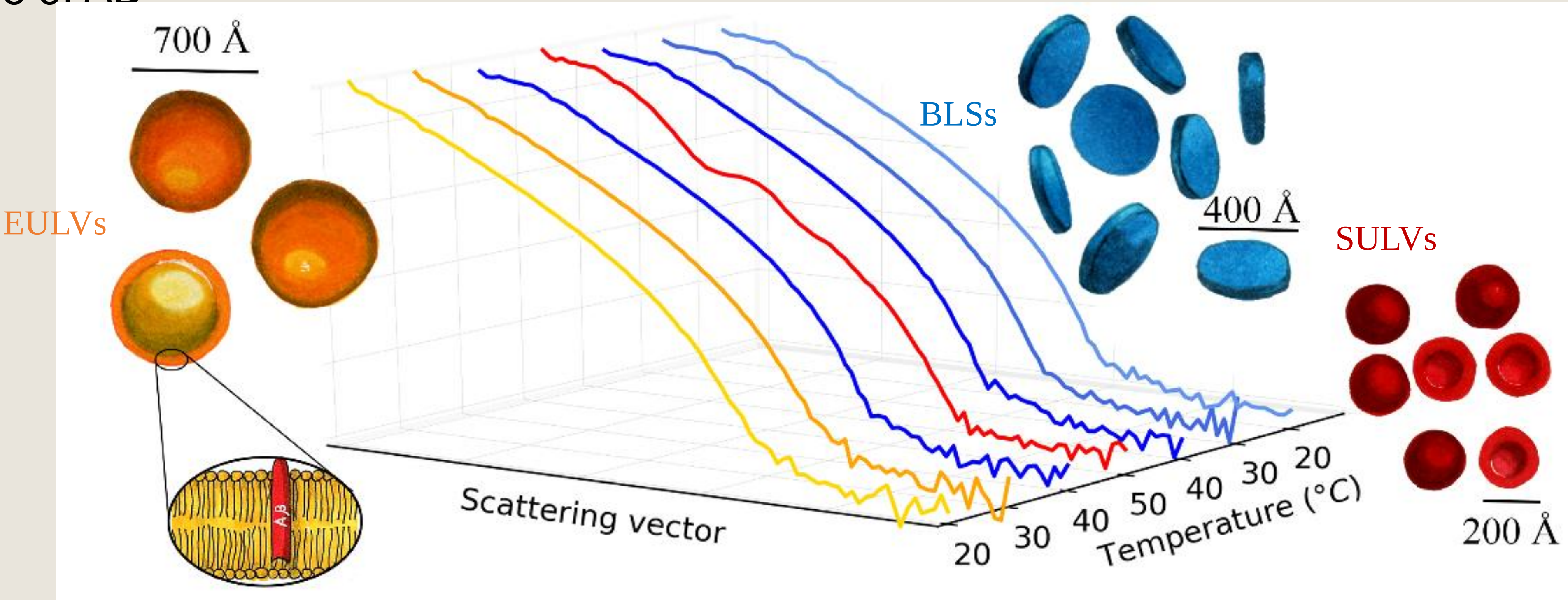
J.Huran, P.Boháček, V.N.Shvetsov, A.P.Kobzev, et al. PSSA (2013)
I.Bolshakova, S.Belyaev, M.Bulavin, et al. Nucl. Fusion 55 (2015)

Residual stresses born by welding in surveillance specimens can be determined by **neutron diffraction**

G.D.Bokuchava, et al. Metals 10 (2020)

Understanding the Mechanism of Alzheimer’s Disease

- Neutron scattering allows to study model membranes that replicate **pre-clinical** stage of AD

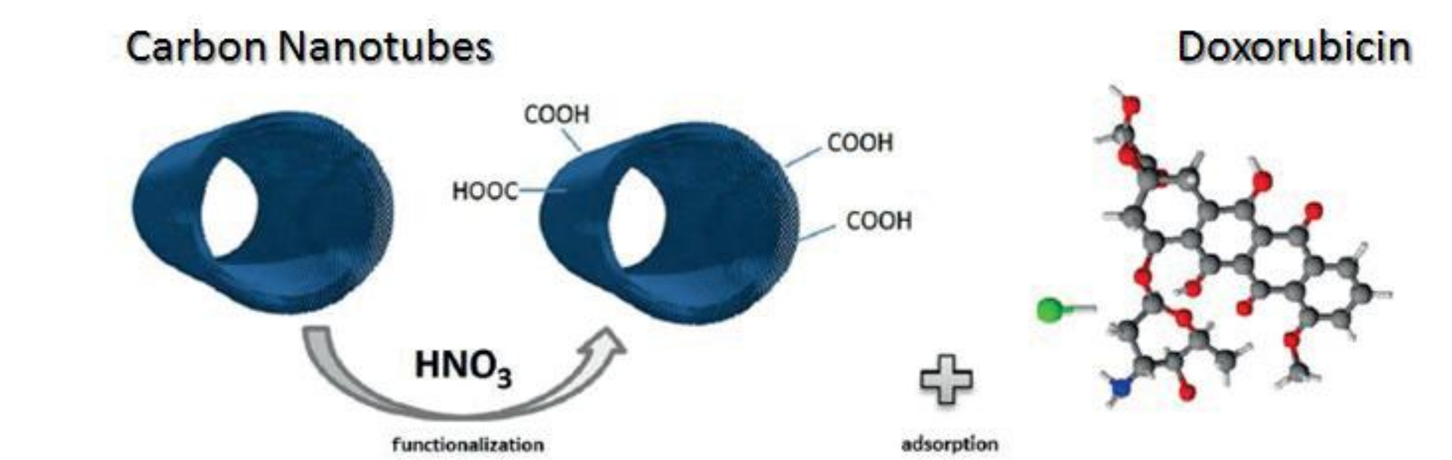


Changes in the membrane self-organization happen during the thermodynamic phase transitions of lipids and are interpreted as the **peptide driven membrane breakage**.

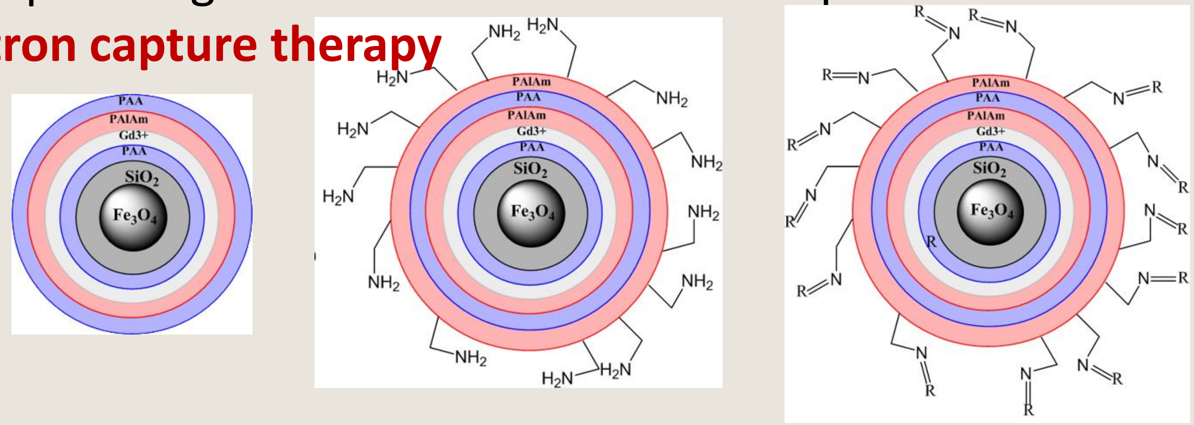
Ivankov, Murugova, Ermakova, Kondela, Badreeva, Soloviov, Kuklin, Kučerka, Sci Rep 11, 21990 (2021)

Drug Delivery Systems

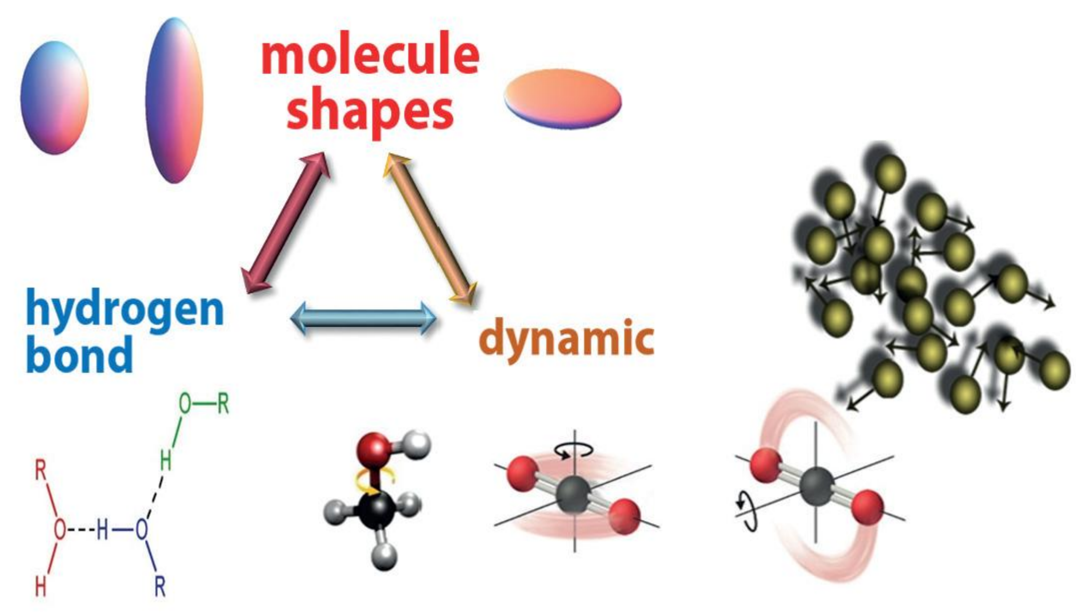
- **Carbon nanoplatforms** for molecular imaging, tissue engineering, biosensors, and **targeted drug delivery** in cancer treatment



- Superparamagnetic Fe3O4 core-shell nanoparticles for **boron neutron capture therapy**



- **Isomeric forms** of antiepileptic drug ETX was studied by **inelastic neutron scattering**
- Due to different pharmacological activity, enantiomers may differ in **toxicity**



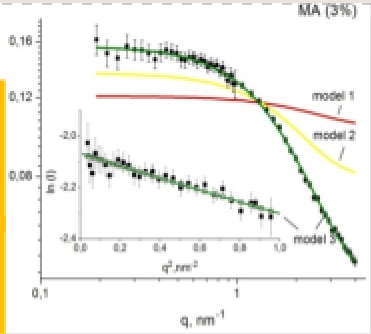
Osiecka N. et al., J. Pharmac. Science. 108, 1 (2019)

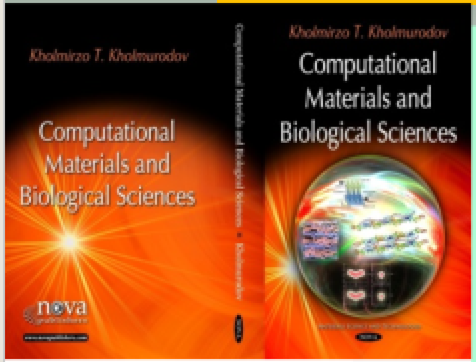
Combined Molecular Dynamics Simulations and Experimental Analysis

04-4-1142-2021/2025

List of projects: **Investigations of functional materials and nanosystems using neutron scattering**; Leaders: D.P. Kozlenko, V.L. Aksenov, A.M. Balagurov

List of activities: **4. Computer simulation of structure and properties of new functional materials and nanosystems**; Leaders: A. Pawlukojc, Kh.T. Kholmurodov

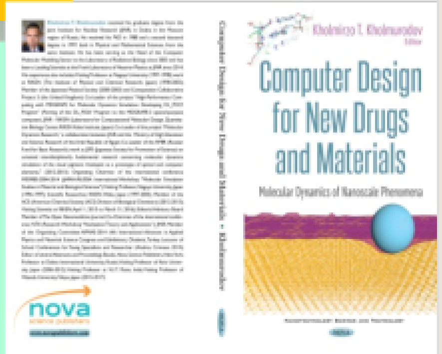


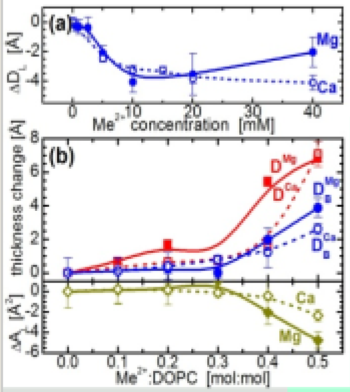


The area of research & topics:

Performing the classical MD and qMD simulations for the condensed matter and biological problems

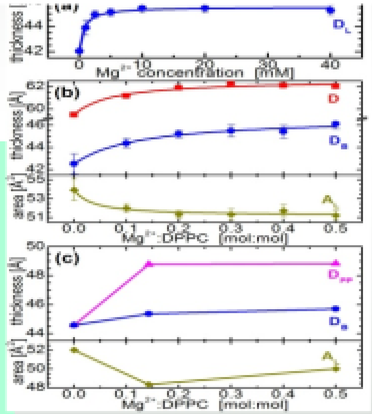
(lipid membranes; cation-zwitterionic lipid interactions; the solvent pH influence on protein conformations; the oxide surfaces with biocompatibility properties; (protein,DNA)/surface interaction processes; the first principles calc. of the structure & electronic characteristics of nanomaterials nanosystems; educ. activities).





Our international collaborations:

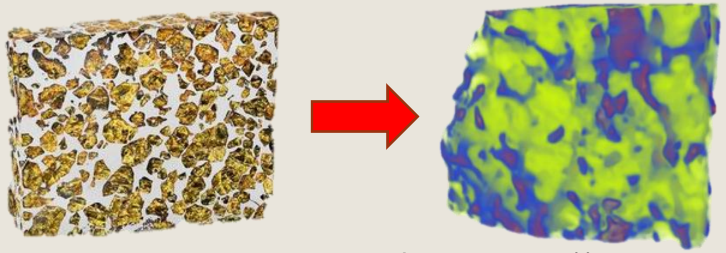
JINR-Japan: RIKEN, Universities of Nagoya, Keio-Yokohama, Waseda-Tokyo.
JINR-India: National Institute of Technologies, Patna.
JINR-Egypt: National Research Center, Cairo.
JINR-Tajikistan: TTU, Phys-Tech. Inst., NA RT, Dushanbe.



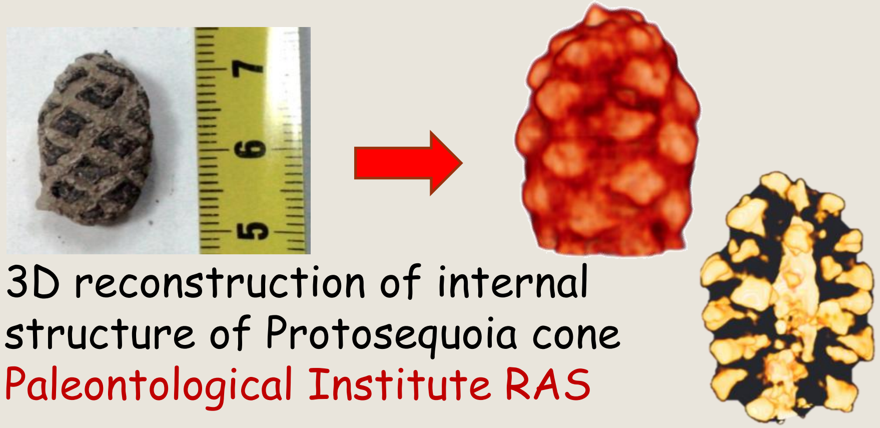
Report by Kh. Kholmurodov at this workshop

Neutron Imaging applied to Cultural Heritage

Radiography
&
Tomography



3D reconstruction of Fe-Ni alloy distribution in Seimchan meteorite



3D reconstruction of internal structure of Protosequoia cone
Paleontological Institute RAS

Neutron tomography reconstructed model with “hidden” gilding pattern of old-russian ancient bracelet dated to XIV century

Nuclear physics with neutrons at FLNP

Nuclear physics: areas of research

- Searching for parity violations in nuclear reactions
- Fission physics
- Investigation of neutron resonances
- Studies of (*n*,*n'*), (*n*,2*n*), (*n*,*p*) and (*n*,*α*) reactions
- Physics of cold and ultracold neutrons, neutron optics
- Applied research.

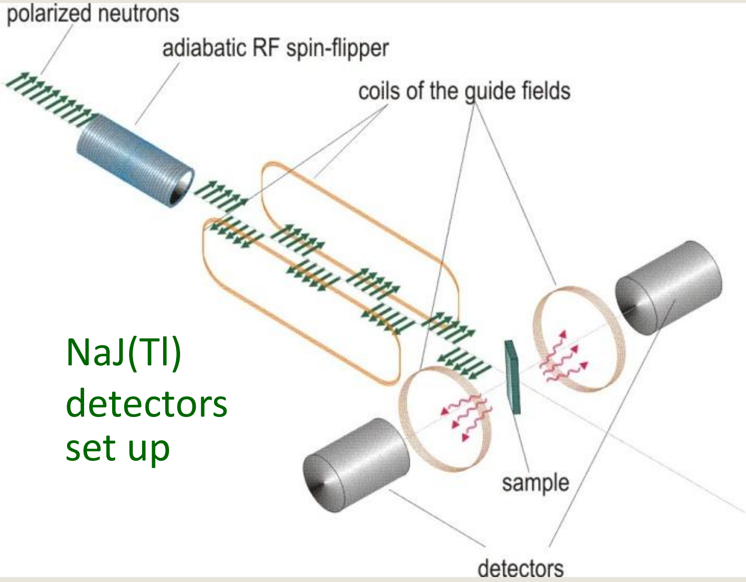
Search for the weak neutral current in the nucleon-nucleon interaction P-odd effects

Determination of the fπ weak neutral current coupling constant from the experimental P-odd correlations

Experiments are performed at ILL (Grenoble)

10B(n,α)7Li* → 7Li + γ (Eγ = 0.478 MeV)
γ-ray asymmetry

expected value $\alpha_\gamma = 5.2 \cdot 10^{-8}$ (DDH)

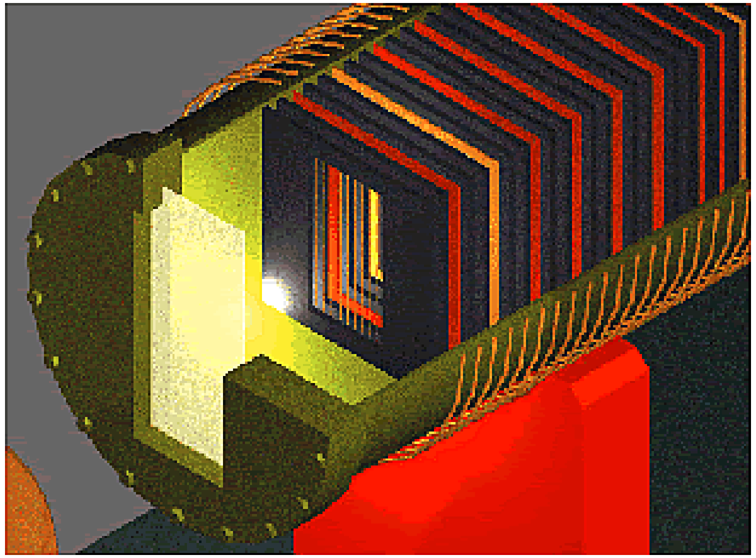


NaJ(Tl) detectors set up

Result of previous runs: main run: $\alpha = (0.0 \pm 2.6) \cdot 10^{-8}$

6Li(n,α)3H
triton-asymmetry

expected value $\alpha_t = -2.7 \cdot 10^{-7}$ (DDH)

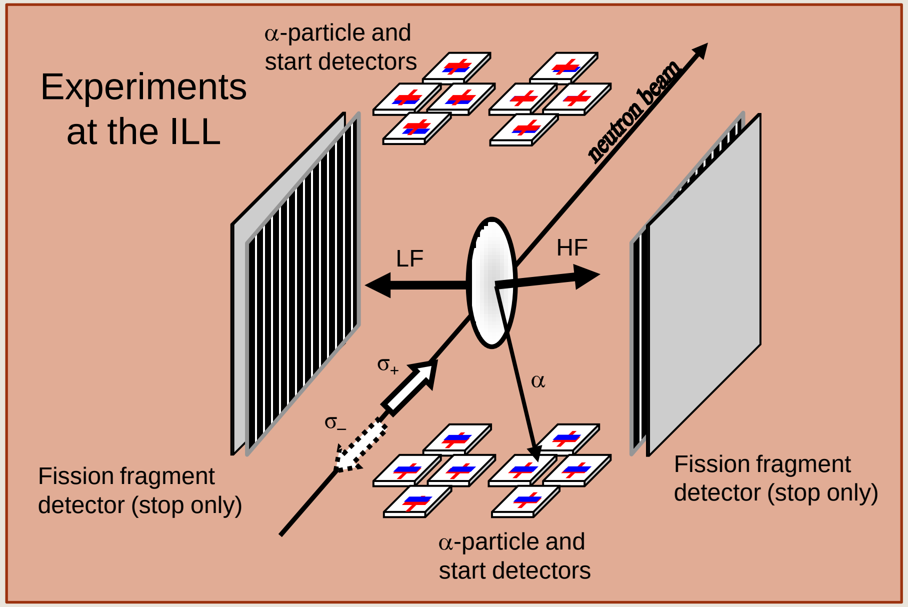


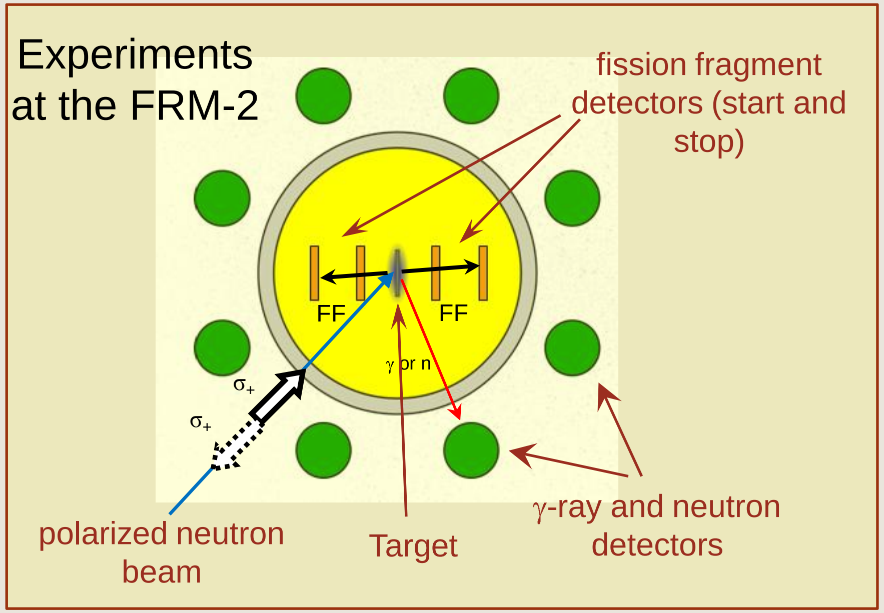
Multisection ionization chamber

Result of previous run: $\alpha = -(8.1 \pm 3.9) \cdot 10^{-8}$

Measurements of T-odd effects in the polarized neutron induced fission

Experiments are performed at the ILL reactor in Grenoble and FRM-2 reactor in Munich in large international collaborations





ROT- and TRI-effects for the α-particle emission

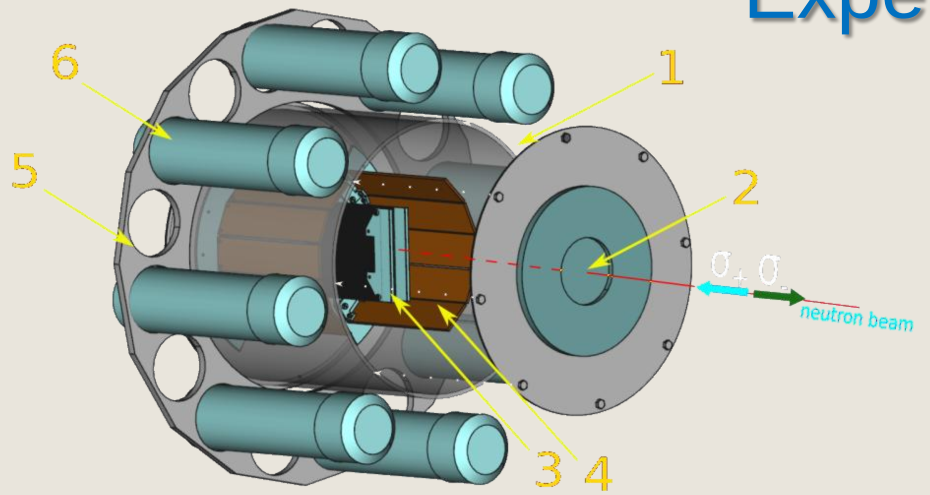
nuclei	spin	ROT (degree of rotation)	TRI (x 10^{-3})
^{233}U	2+, 3+	0.03(1)	-3.9(1)
^{235}U	3-, 4-	0.215(5)	1.7(2)
^{239}Pu	0^+, 1^+	0.020(3)	-0.23(9)

ROT-effect for the γ-ray and neutron emission

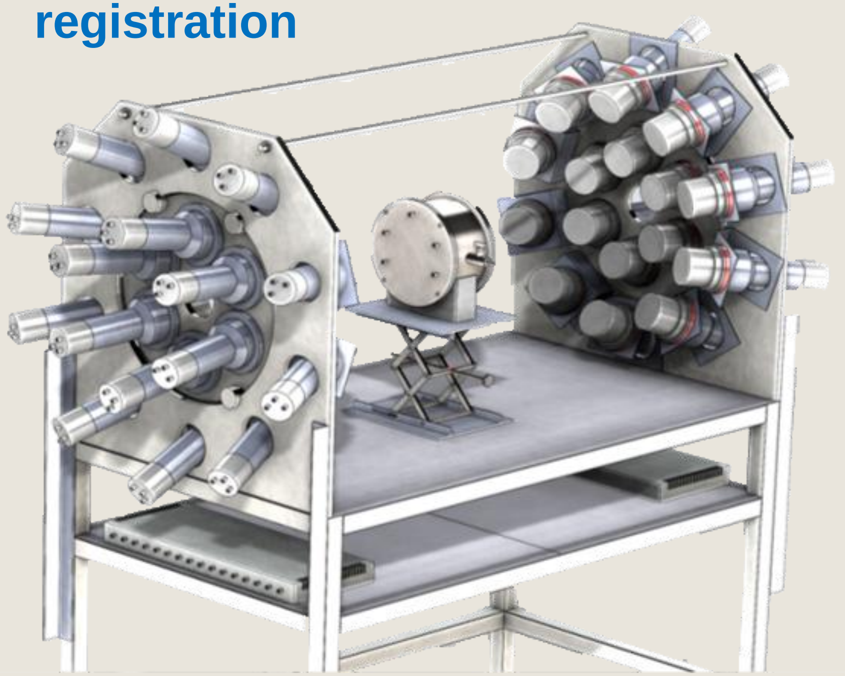
nuclei	Angle to the fission axis	γ-rays (x10^{-5})	Neutrons (x10^{-5})
^{233}U	22.5	+2.8±1.7	+4.8±1.6
^{235}U	22.5	-12.9±2.4	-21.2±2.5

Nuclear fission studies

Experimental setups

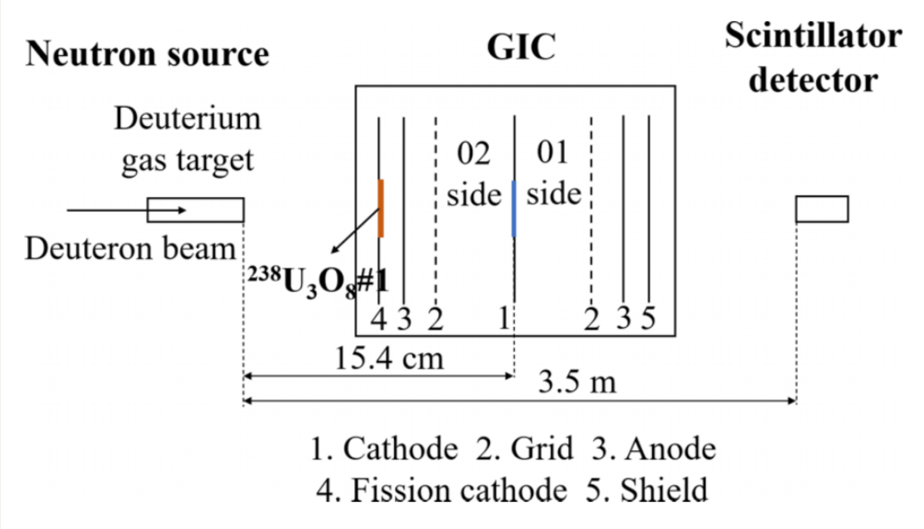


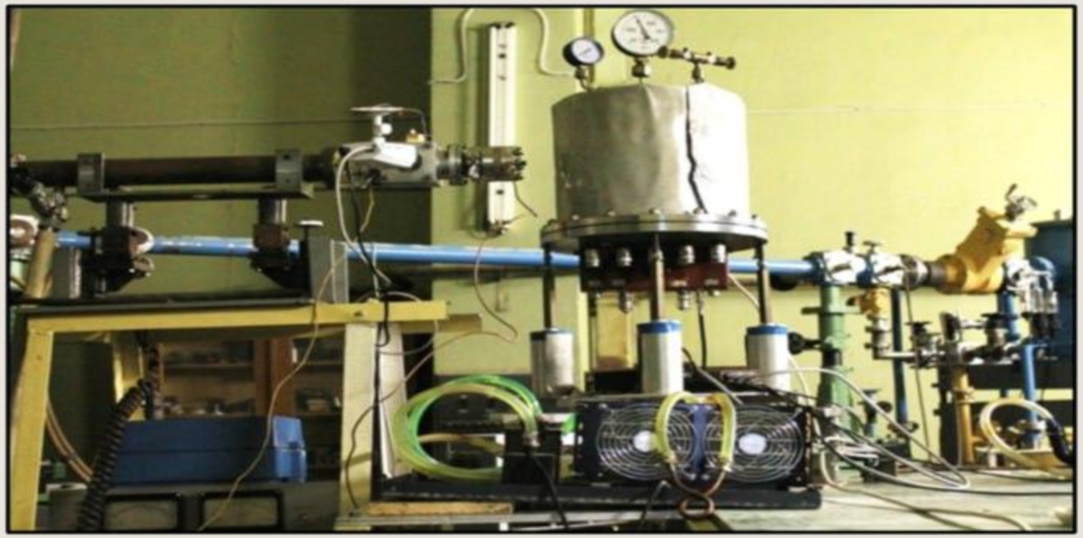
- Experimental setup for studying of fission neutron multiplicity and fragment mass distribution
- To measure mass distribution a position-sensitive ionization chamber is used
- BC501 scintillators are used for neutron registration



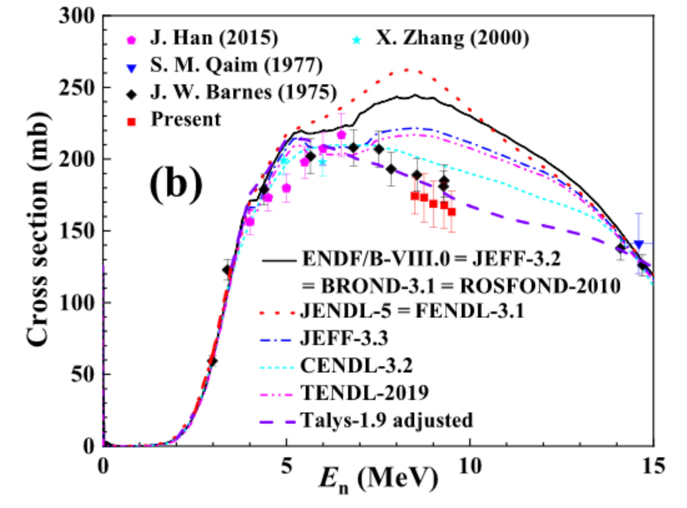
- Experimental setup for ROT-effect study
- 1 — fission chamber, 2 — Al input chamber window, 3, 4 — fission fragment detectors based on position-sensitive multiwire proportional counters (start and stop detectors), 5 — holder, 6 — scintillation plastic detectors of γ-quanta and neutrons
- Angular distributions of γ-quanta, neutrons and fission products are measured

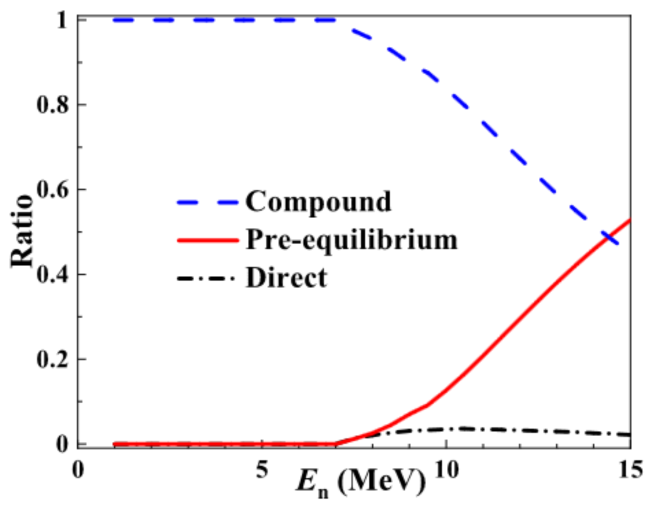
Measurements on (n,p), (n,α) reaction cross sections



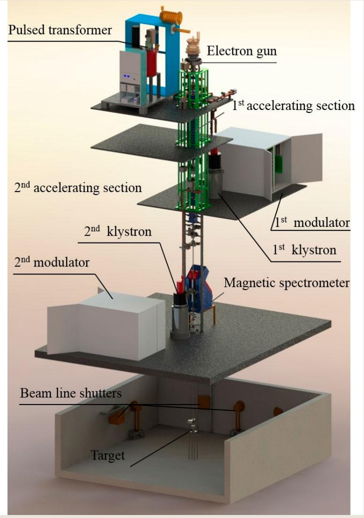


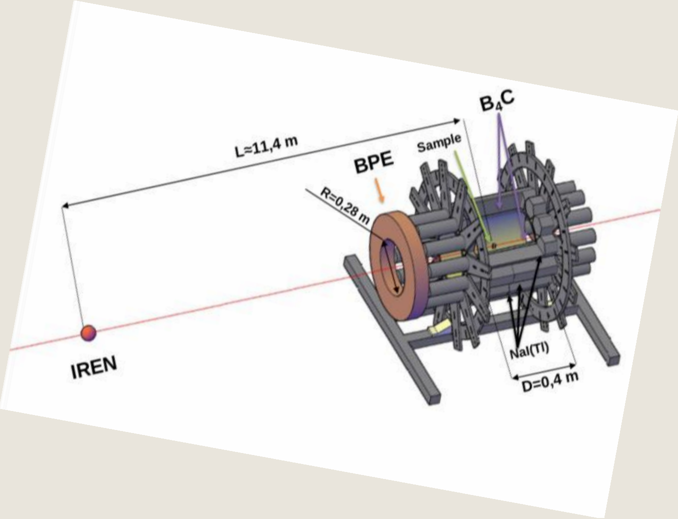
- Experimental setup for (*n,α*) investigation
- ion. chamber is used to measure energies of *α*
- 238U for neutron fluence monitoring, n-detector for measurement of n-energy
- Estimation of nuclear reaction mechanisms impacts in result



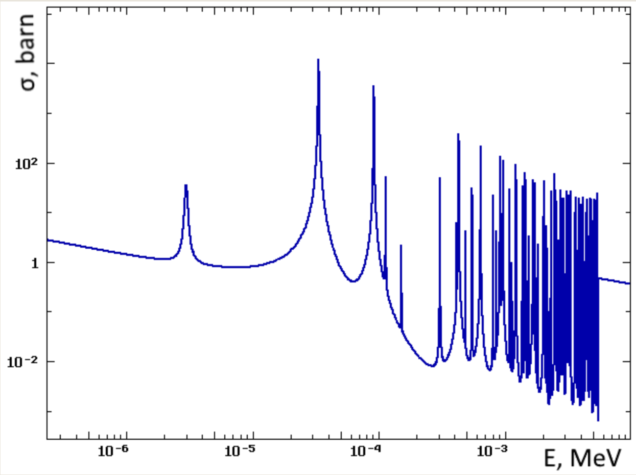


The use of resonance neutron method for investigating parts of the “Proton” rocket engine

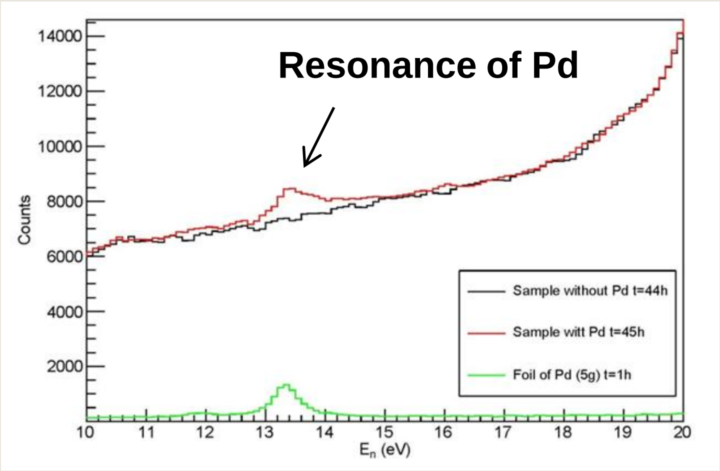




One hypothesis for crash of the Proton rocket is presence of palladium in some critical components of the engine

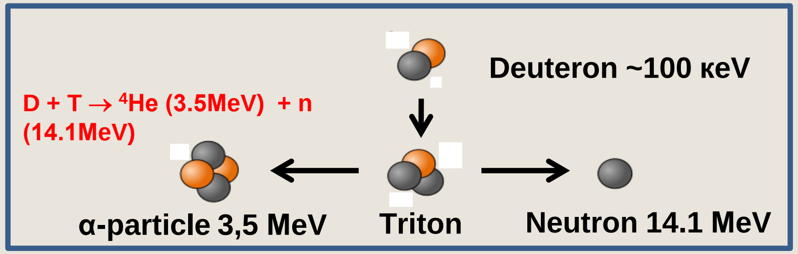


Neutron resonances

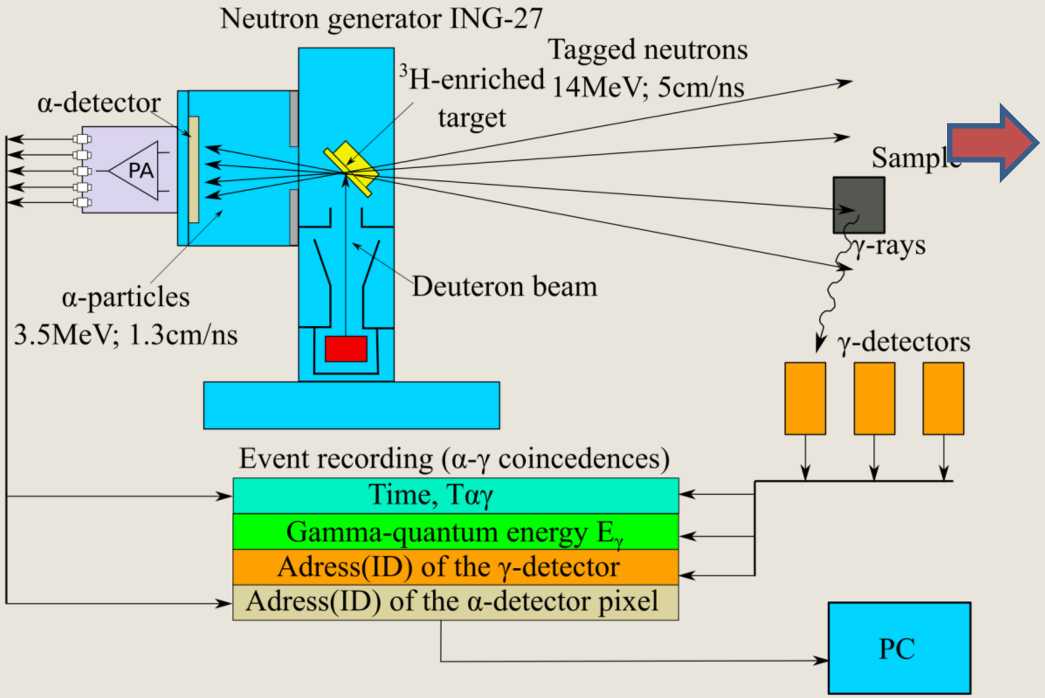


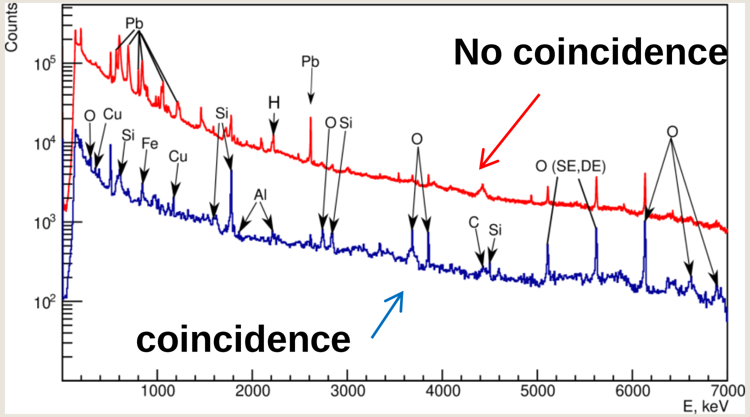
The amount of Pd in the ~60 g sample was found to be 98 ± 10 mg.

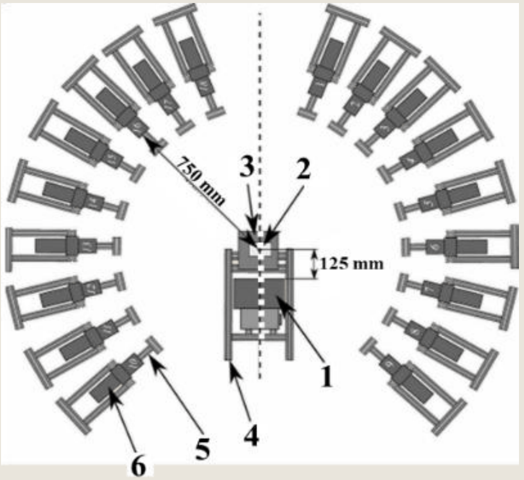
Project TANGRA: using the tagged neutron method

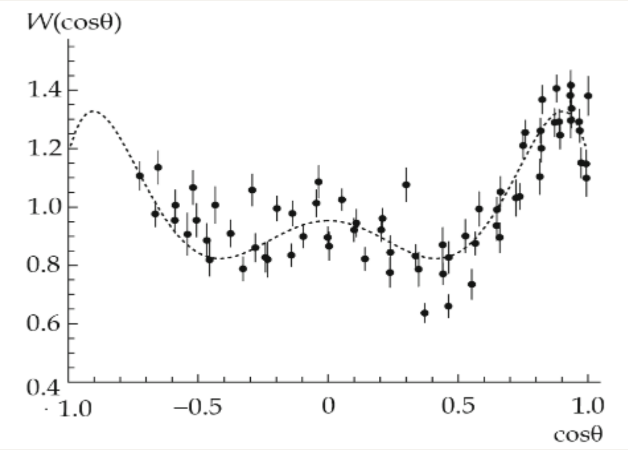


Neutron generator ING-27









Measured angular distribution for 6.13 MeV transition in oxygen.

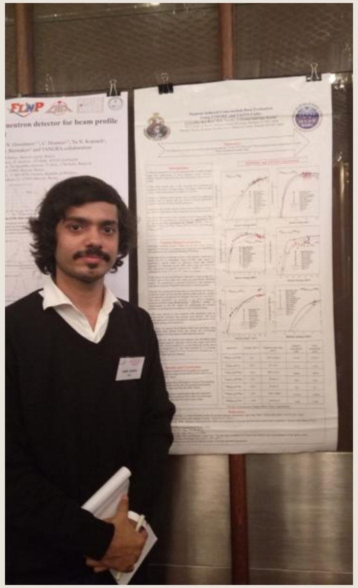
Elements can be identified by their characteristic spectra.

Project TANGRA: JINR – India cooperation

Common project: Fast Neutrons as a probe for Elemental Analysis, Nuclear Reaction Studies and Cross Section Measurements

JINR participants: Yu.N. Kopatch, V.M. Bystritsky, P. V. Sedyshev, V.R. Skoy, I.N. Ruskov, D.N. Grozdanov, N.A. Fedorov, F.A. Aliyev, C. Hramco, S. B. Borzakov, A.O. Zontikov

Indian participants: A. Kumar, A. Gandhi (BHU) N. Singh, S. Mukherjee (MSU, Baroda), M. Nandy (SINP, Kolkata), A. Chakraborty (Visva Bharti, Shantiniketan)

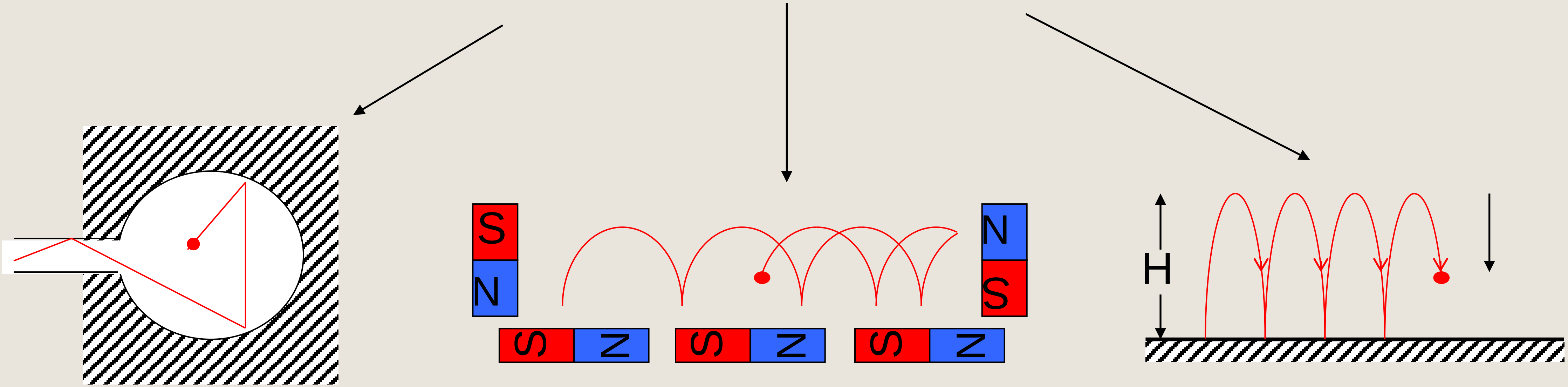


Aman Gandhi Banaras Hindu University

PH.D. (Experimental Nuclear Physics) (**Title:** “Study of neutron induced reaction cross section for reactor building materials”) **Supervisor**: Dr Ajay Kumar

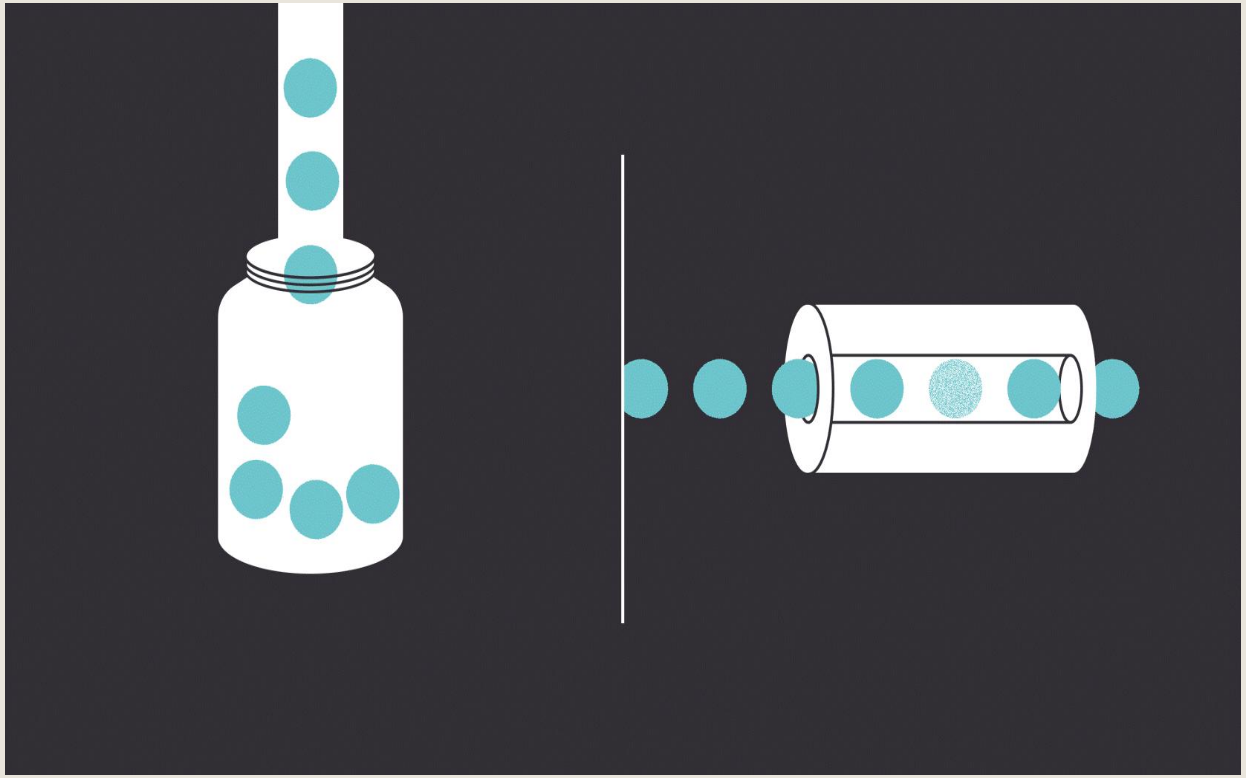
Ultracold neutrons (UCN)

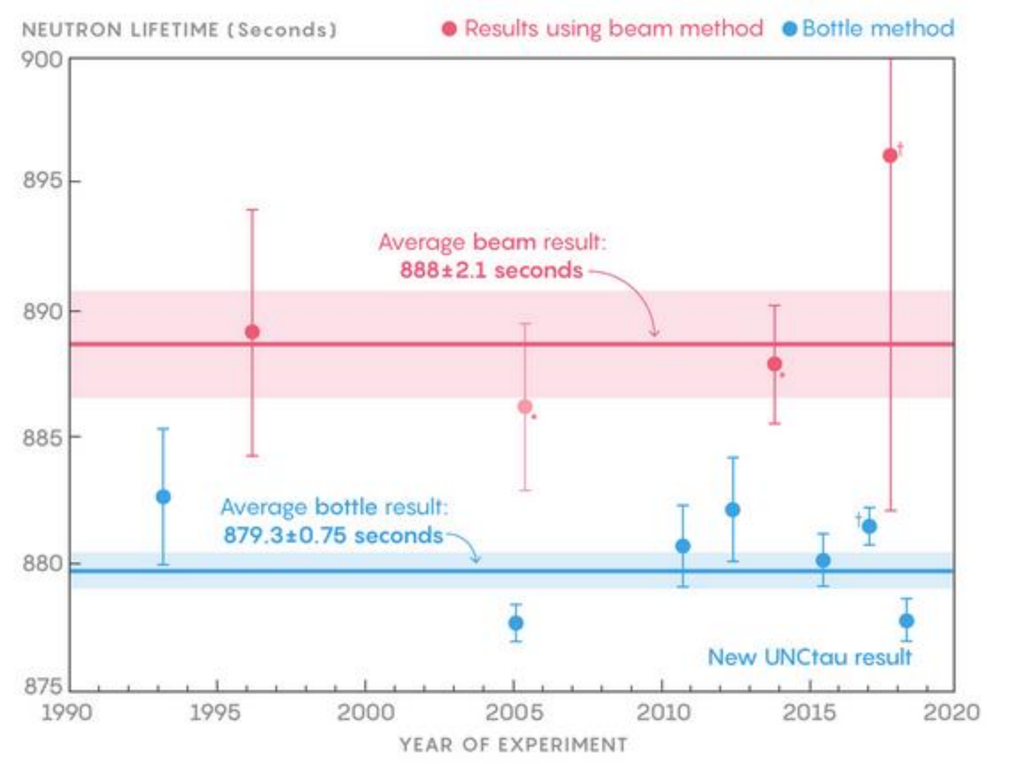
Potential of interaction of slow neutrons with matter :



Effective potential	~ **10^{-7} eV**
Gravity:	~ **10^{-7} eV** / Meter
Magnetic field:	~ **10^{-7} eV** / Tesla

Measurements of the neutron lifetime τ_n





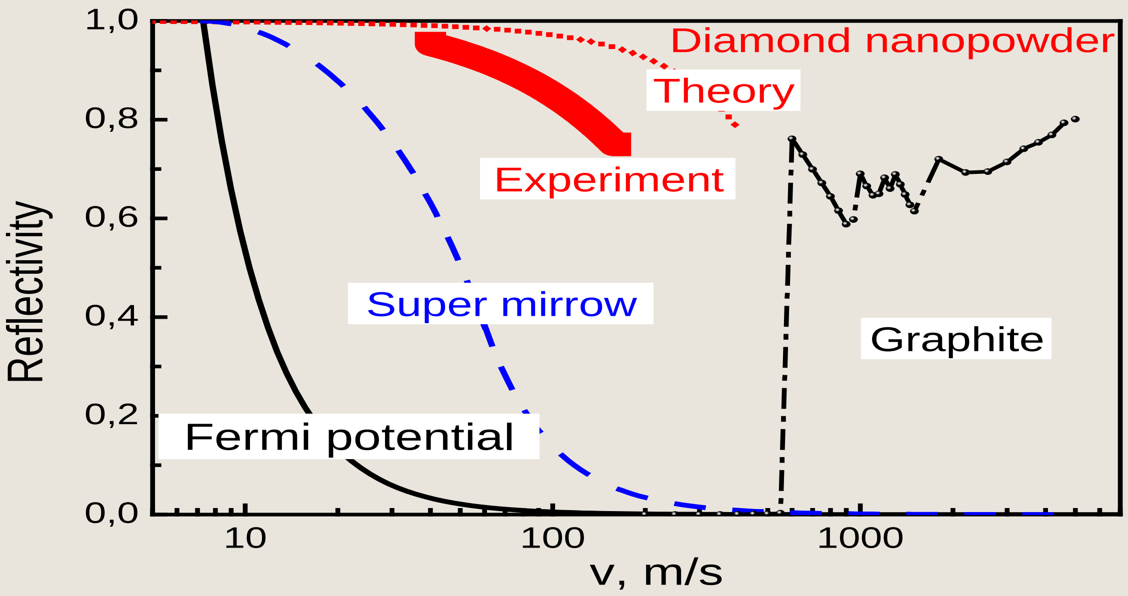
Storage experiments with UCN   Beam experiments with cold neutrons

Neutron Lifetime Puzzle

Reflection of Cold Neutrons by Nanoparticles

Efficient elastic reflection of VCN (λ>25Å) at diamond nanoparticle powders (d~ λ)

Nano-diamond trap



Could be used:

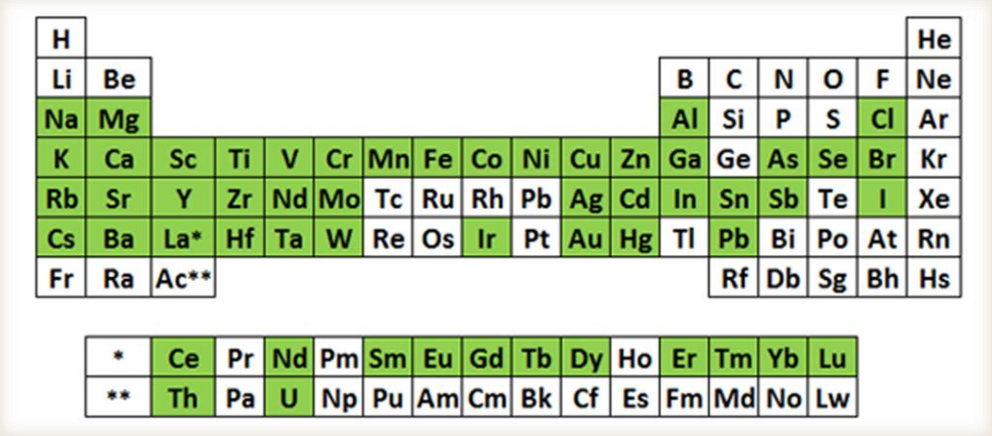
•Storage of very cold neutrons

dozens of times possible increasing neutron density

•Using as reflector in cold neutron souse

dozens of times more intensive VCN and UCN source

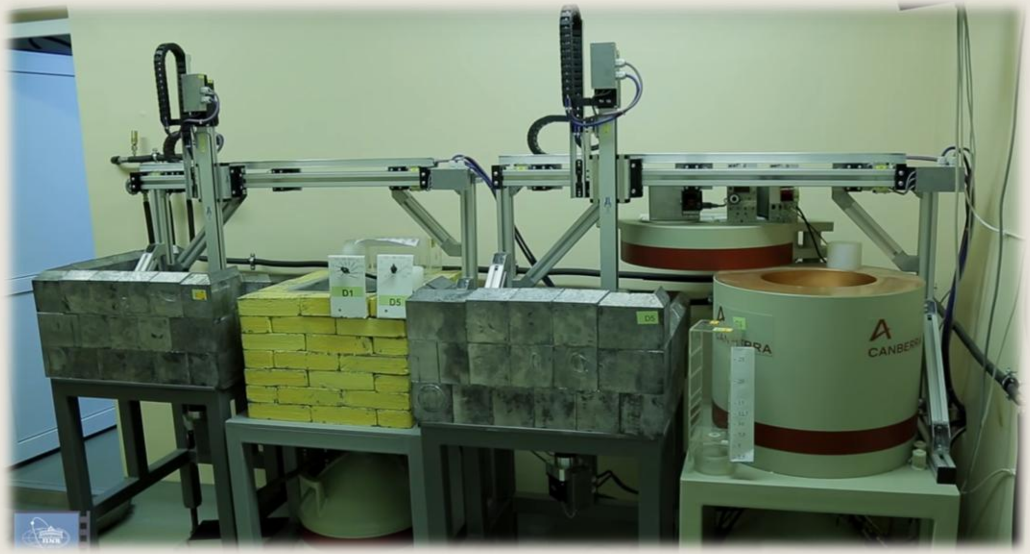
Neutron activation analysis at FLNP



- Neutron activation analysis is a very sensitive (ppb) method of elemental analysis based on $^{A}Z(n,\gamma)$ – products measurement
- In FLNP this method is implemented at REGATA and REGATA-2 facilities

The Main Areas of Research

- Quality control of the air (study of aerosol filters, biomonitoring with mosses, lichens, etc.)
- Assessment of terrestrial and aquatic ecosystems (soil, sediments, biota)
- Geology and Geoecology
- Foodstuffs
- Materials Science (new and ultra–pure materials, new technologies)
- Biotechnology (development of new medicines and sorbents)
- Archaeology



Atmospheric Deposition of Trace Elements

1993: Biomonitoring…

M.V. Frontasyeva, V.M. Nazarov and E. Steinnes. **Mosses as monitors of heavy metal deposition: Comparison of different multi-element analytical techniques.** In R.J. Allan and J.O. Nriagu, eds., *Heavy Metals in the Environment*, Vol.2, pp. 17-20. CEP Consultants, Edinburgh **1993**.

courtesy of Dr. M.V. Frontasyeva

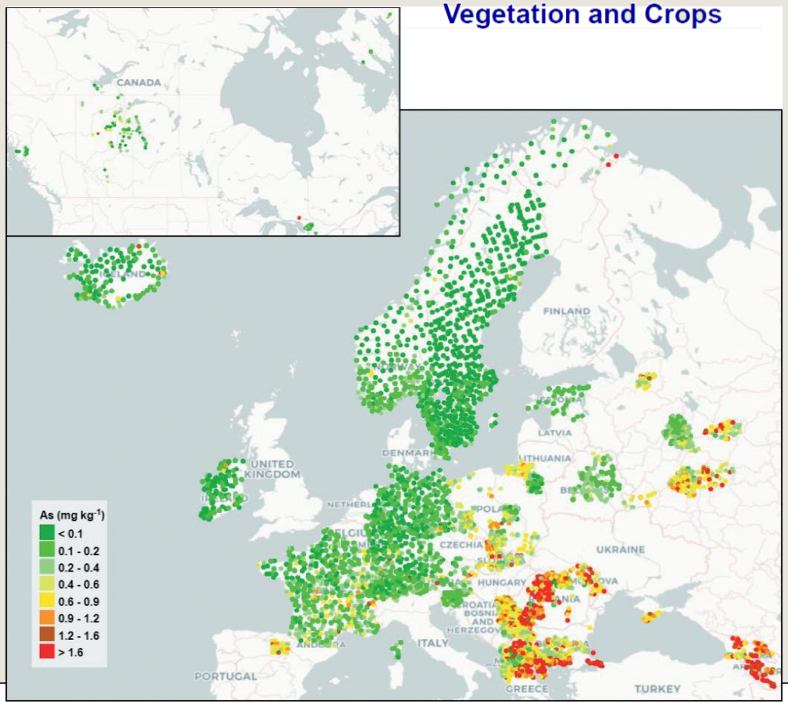
- **Moss** is used as a monitor of **atmospheric pollution** determined using the **Neutron Activation Analysis** detecting **heavy metals** and other trace elements (up to **45** in total)

UNECE

United Nations

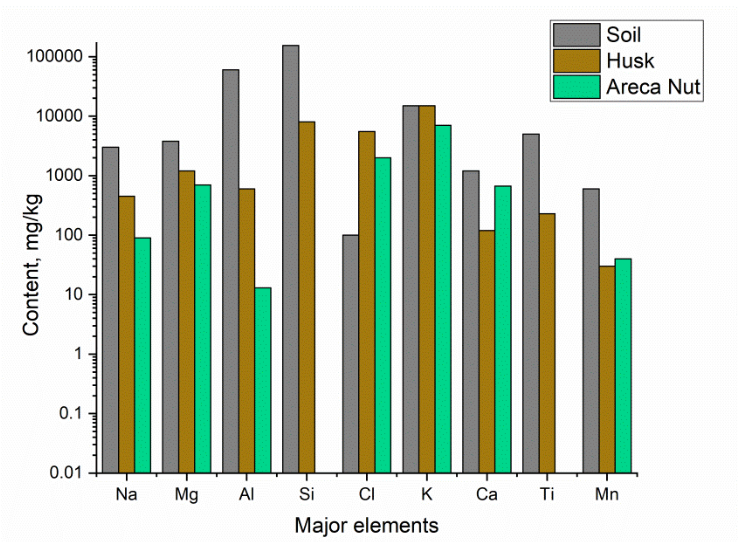
United Nations Economic Commission for Europe

International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops

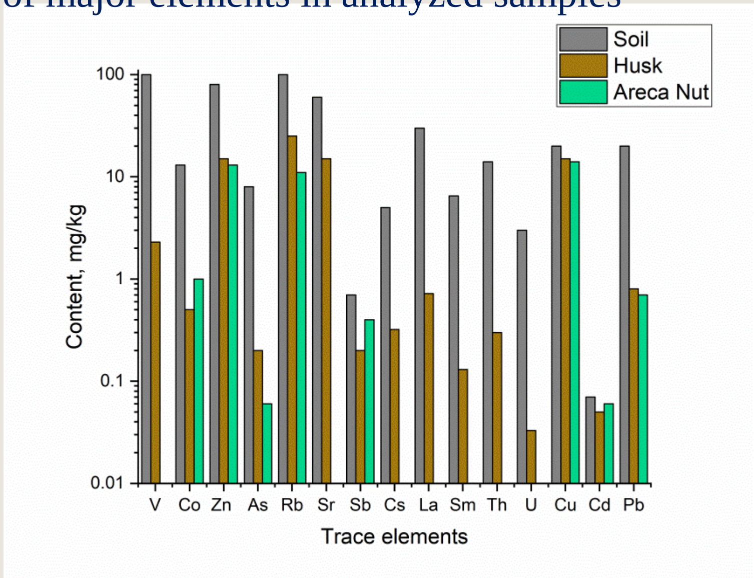


Map of arsenic distribution from the 2015-2016 report

Neutron activation analysis and related analytical techniques in the assessment of products quality



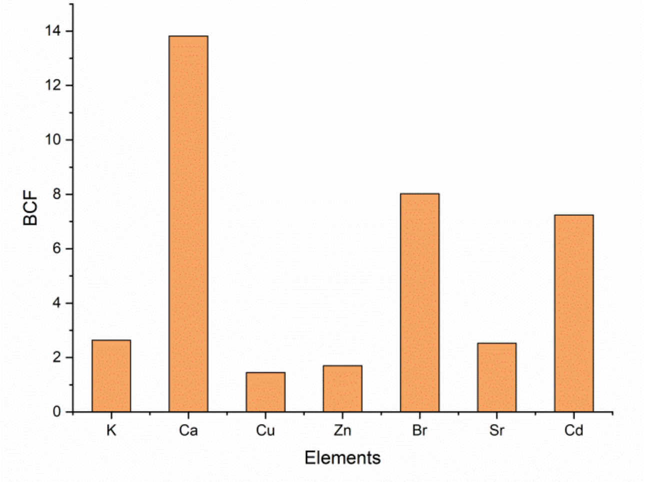
Level of major elements in analyzed samples



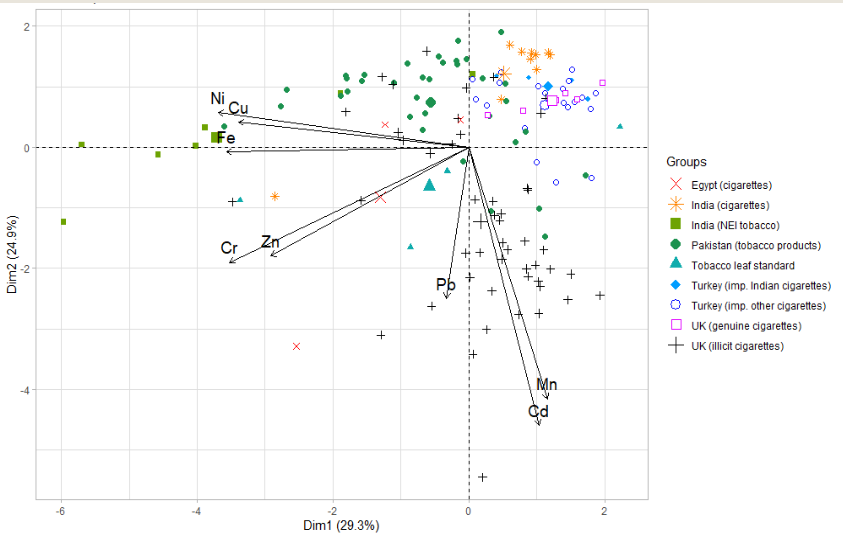
Level of trace elements in analyzed samples

Areca nuts

Collaboration with Mizoram University



Bioconcentration of elements in tobacco

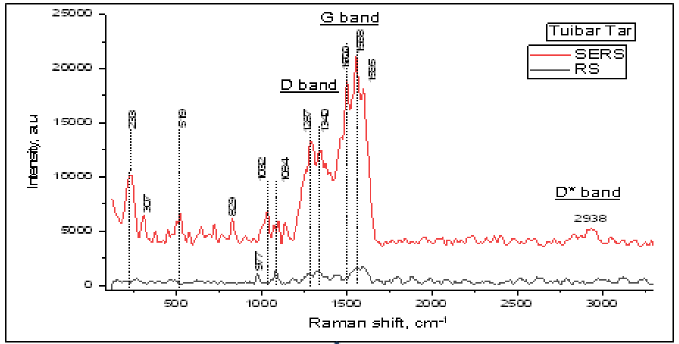


Bi-plots of heavy element distributions in Tobacco samples of different countries

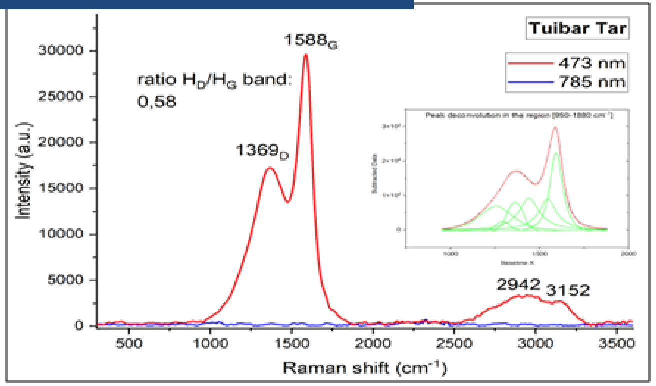
Raman spectroscopy at FLNP

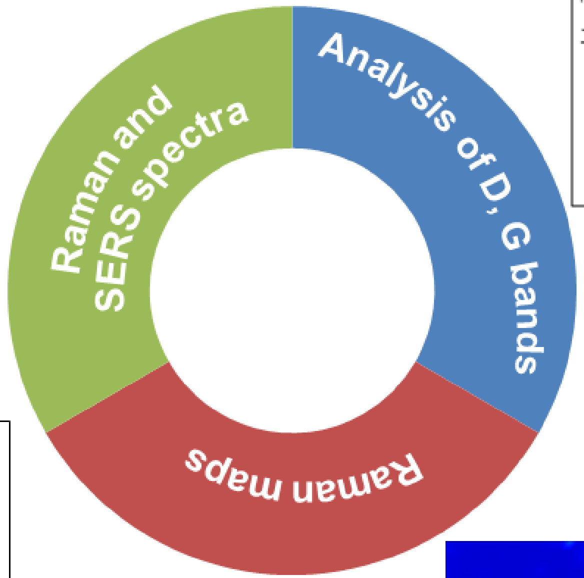
Cooperation with the Department of Chemistry, Mizoram University, Aizawl, INDIA.

TOPIC: Raman spectroscopy of tobacco tar and ash.



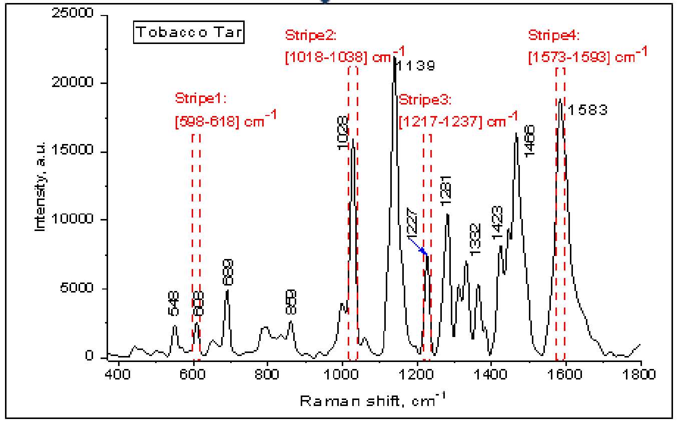
Raman spectrum of tobacco tar with most prominent D and G band.



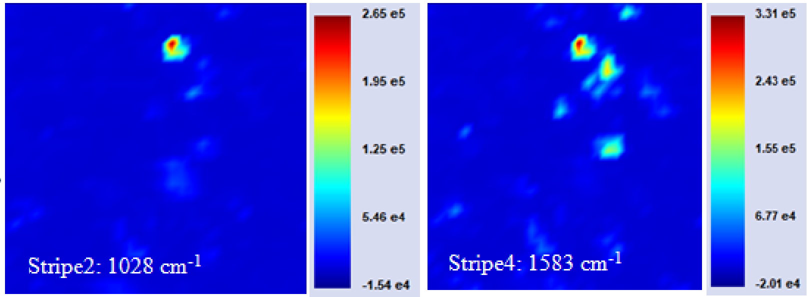


Raman and SERS spectrum of Tobacco Tar on a SERS plate with Ag NPs.

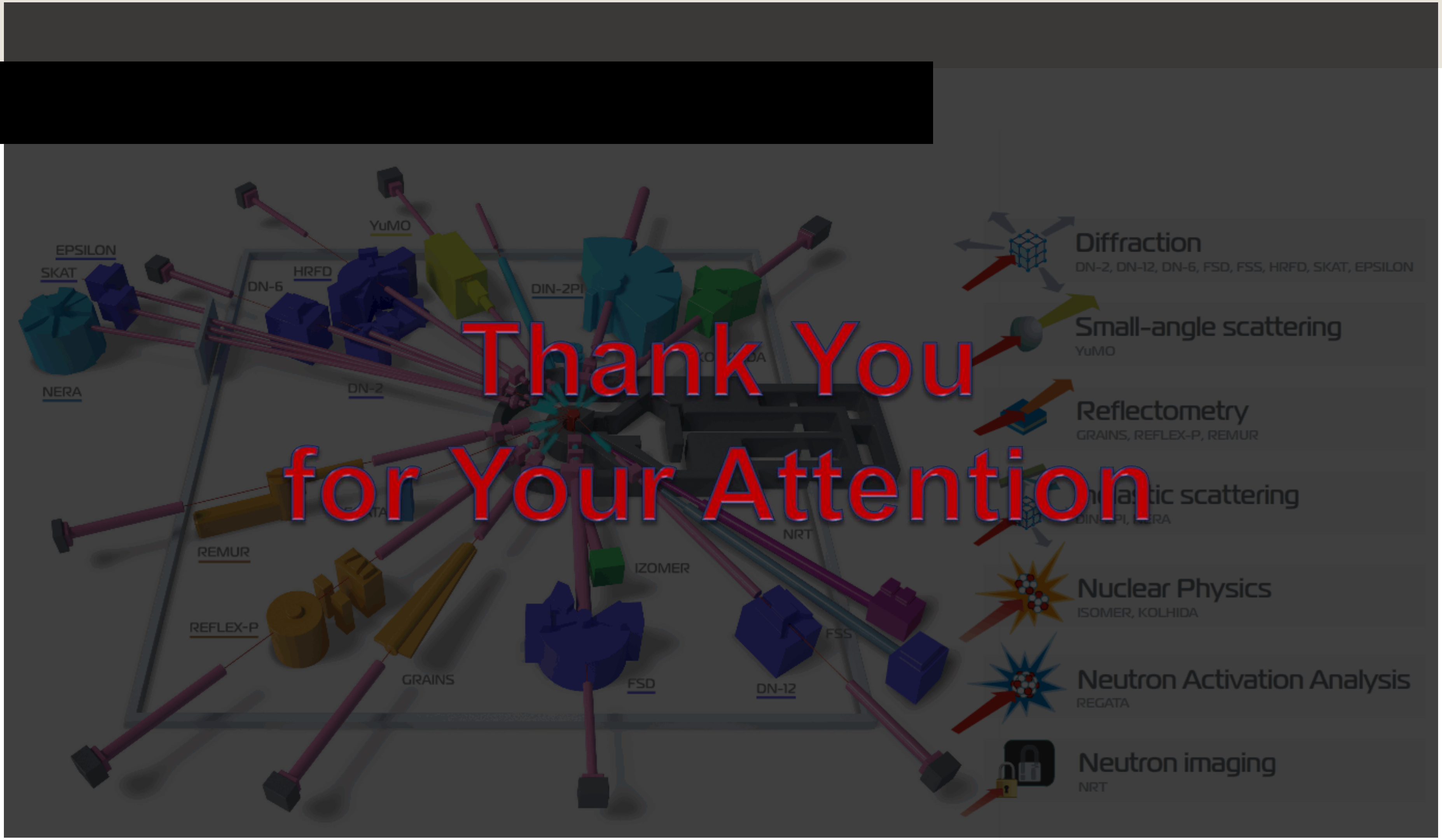
Raman maps with stripes centered at 1028 cm^{-1} associated with the nicotine/nornicotine and 1583 cm^{-1} for G band.



Mapping area 30x30 µm



[redacted]



Thank You for Your Attention