# Frank Laboratory of Neutron Physics

# Joint Institute for Nuclear Research

***Yuri Kopatch***
***Deputy director of FLNP***

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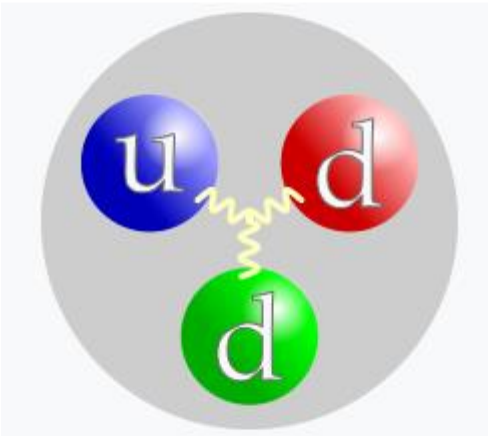
# Neutron main characteristics




The neutron is a subatomic particle, which has a neutral charge, and a mass slightly greater than that of a proton.

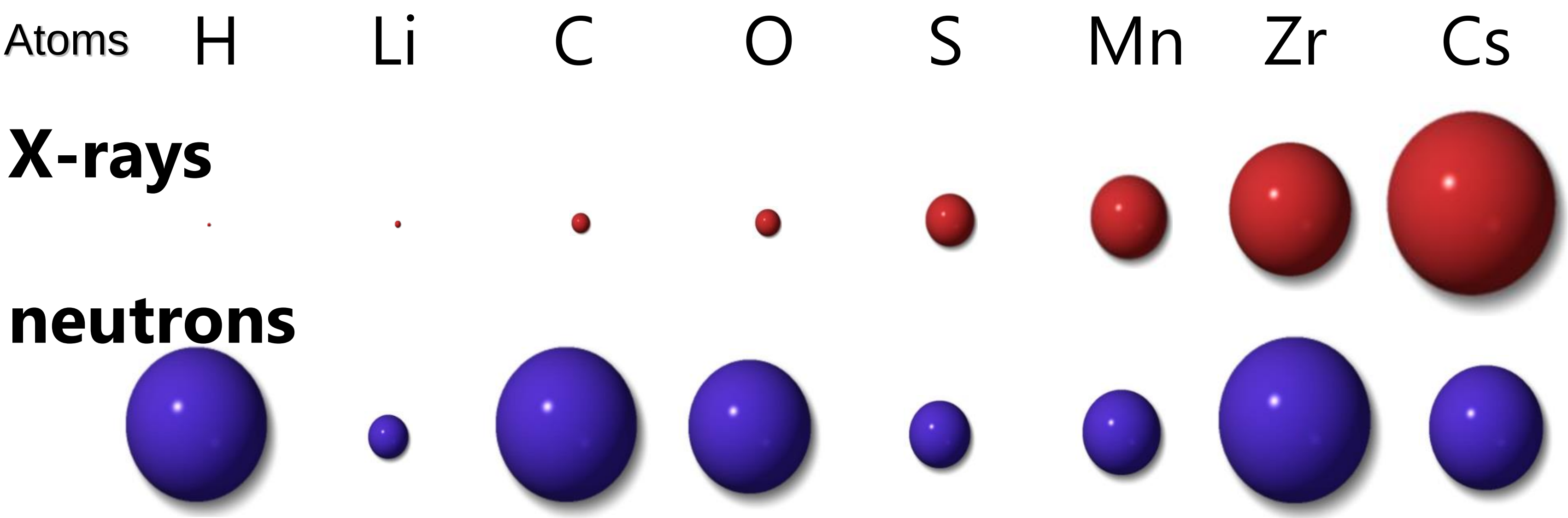
The neutron was discovered by James Chadwick in 1932.

| | |
|---|---|
| **Electric charge** | **0 e** |
| **Mean lifetime** | **879.4(6) s** |
| **Electric dipole moment** | **< 1.8×10−26 e·cm (experimental upper limit)** |
| **Magnetic moment** | **−1.04187563(25)×10−3 $\mu_B$** |
| **Spin** | **1/2** |

# Types of interactions where neutron is involved:

- Strong interaction
  (nuclear reactions)
- Electromagnetic interaction
  (via magnetic moment)
- Weak interaction
  (beta decay)
- Gravitational interaction

# Why neutrons?



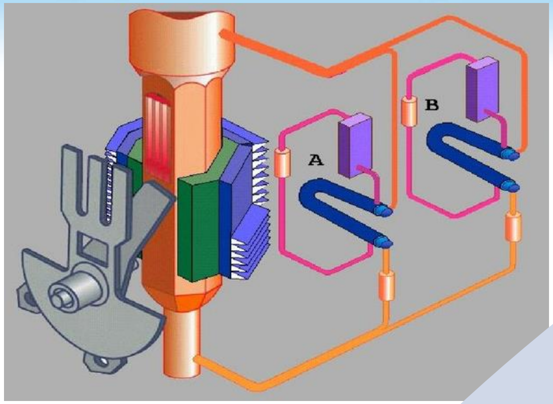

sensitivity to light elements / sensitivity to isotopes

✌Neutrons do not have a charge – a large **penetration ability** : **good for investigation and testing bulk materials without destruction**.

# FLNP – Frank Laboratory of Neutron Physics

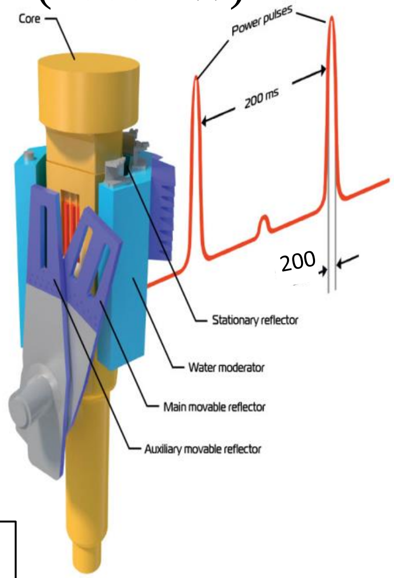
- 506 staff personnel, average age ~47 years;
- ~24 M$ - 2023 annual budget, ~45% - for the research;
- Two scientific directions:
  - Condensed matter physics;
  - Nuclear physics with neutrons;
- Basic facility:
  - **IBR-2 – pulsed research reactor**;
- Other facilities:
  - IREN – resonance neutron source;
  - EG-5 Van de Graaf accelerator;
  - TANGRA (neutron generator ING-27)
  - CARS – Raman microscope;
- About 250 papers published annually;

Ilya Mikhailovich FRANK (1908-1990)



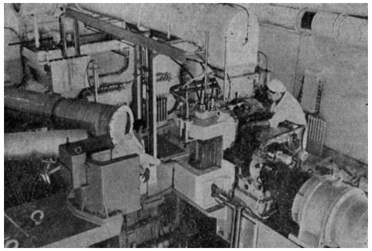

**1989 – 2006 IBR-2**
(1500 – 2000 kW)

**2010 IBR-2 (M)**
(2000 kW)

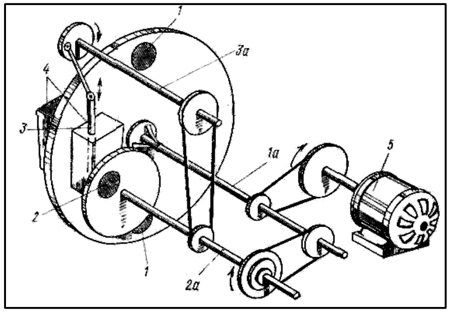



**1970 – 1979 IBR-30,**
Average power - 30 kW

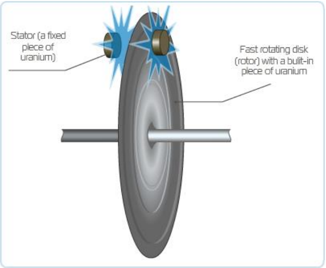
**1980 – 1989 IBR-30 / IBR-2**
(100-1000 kW)



**1960 – 1969 IBR,**
Average power – 1-6 kW



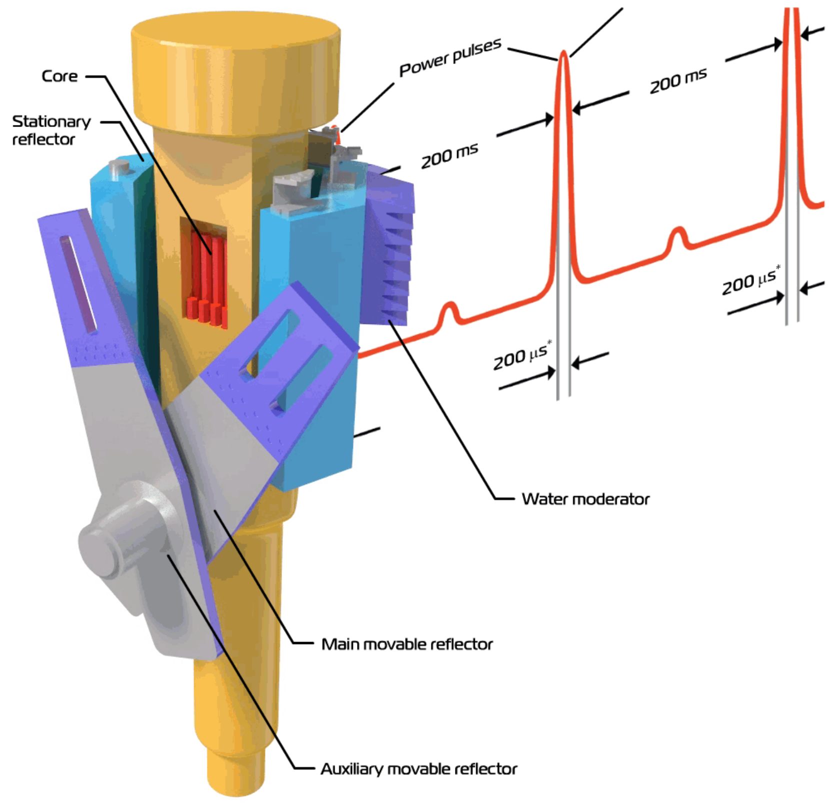
**1957 -** establishment of the LNP




**1956 -** establishment of the Joint Institute for Nuclear Research

**1955 -** The idea of the pulsed fast reactor **Dimitry I. Blokhintsev**

# Pulsed Reactor IBR-2



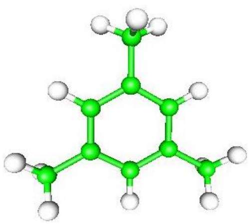

**2500 hours/year**

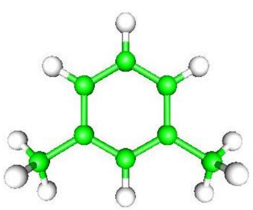
| **Average power, MW** | **2** |
|---|---|
| Fuel | $PuO_2$ |
| Number of fuel assemblies | 69 |
| Maximum burnup, % | 9 |
| Pulse repetiton rate, Hz | 5 |
| Pulse half-width, µs:<br>fast neutrons<br>thermal neutrons | <br>200*<br>340 |
| Rotation rate, rev/min<br>• Main reflector<br>• Auxiliary reflector | <br>600<br>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<br>• Time average<br>• Burst maximum | <br>$\sim 10^{13}$ n/cm$^2$ s<br>$\sim 10^{16}$ n/cm$^2$ s |

# Water Moderators

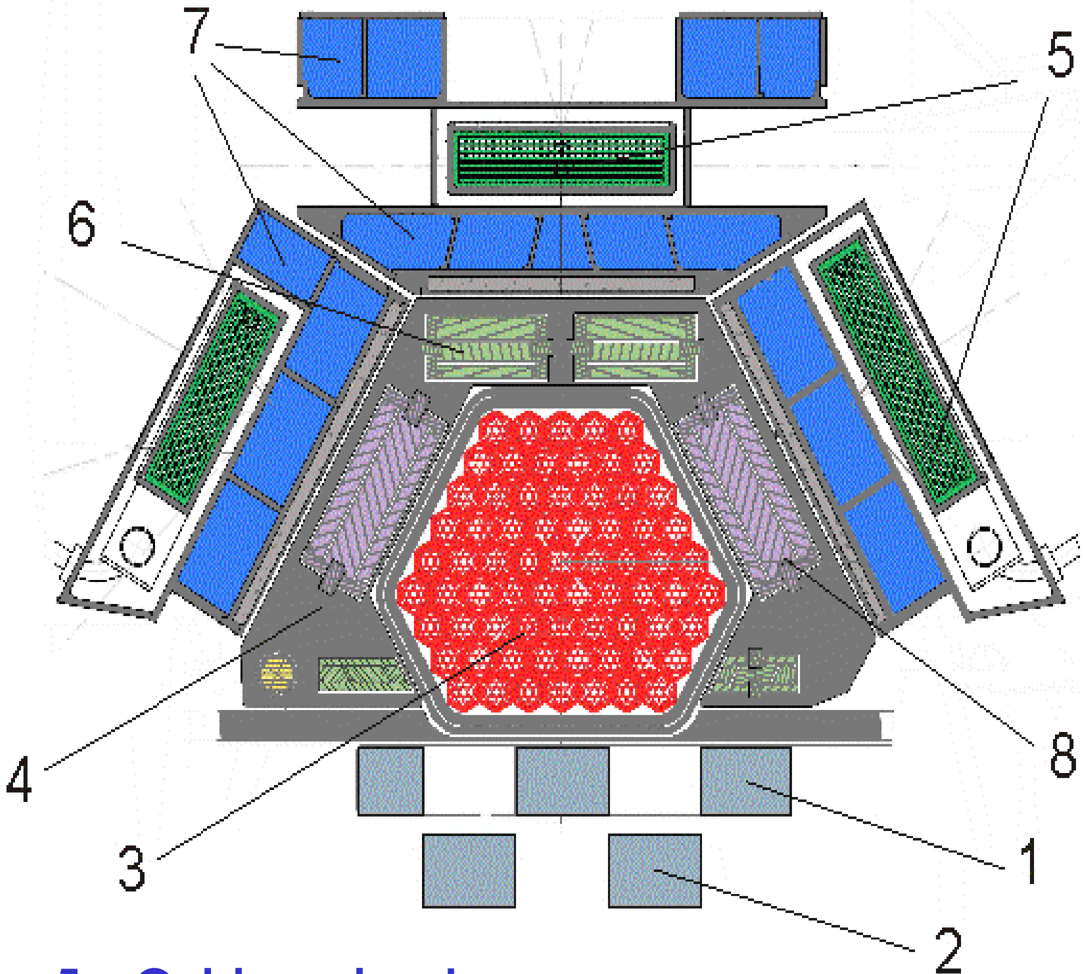
Thermal neutrons
0.025 eV

# Cryogenic moderators
– developed by FLNP





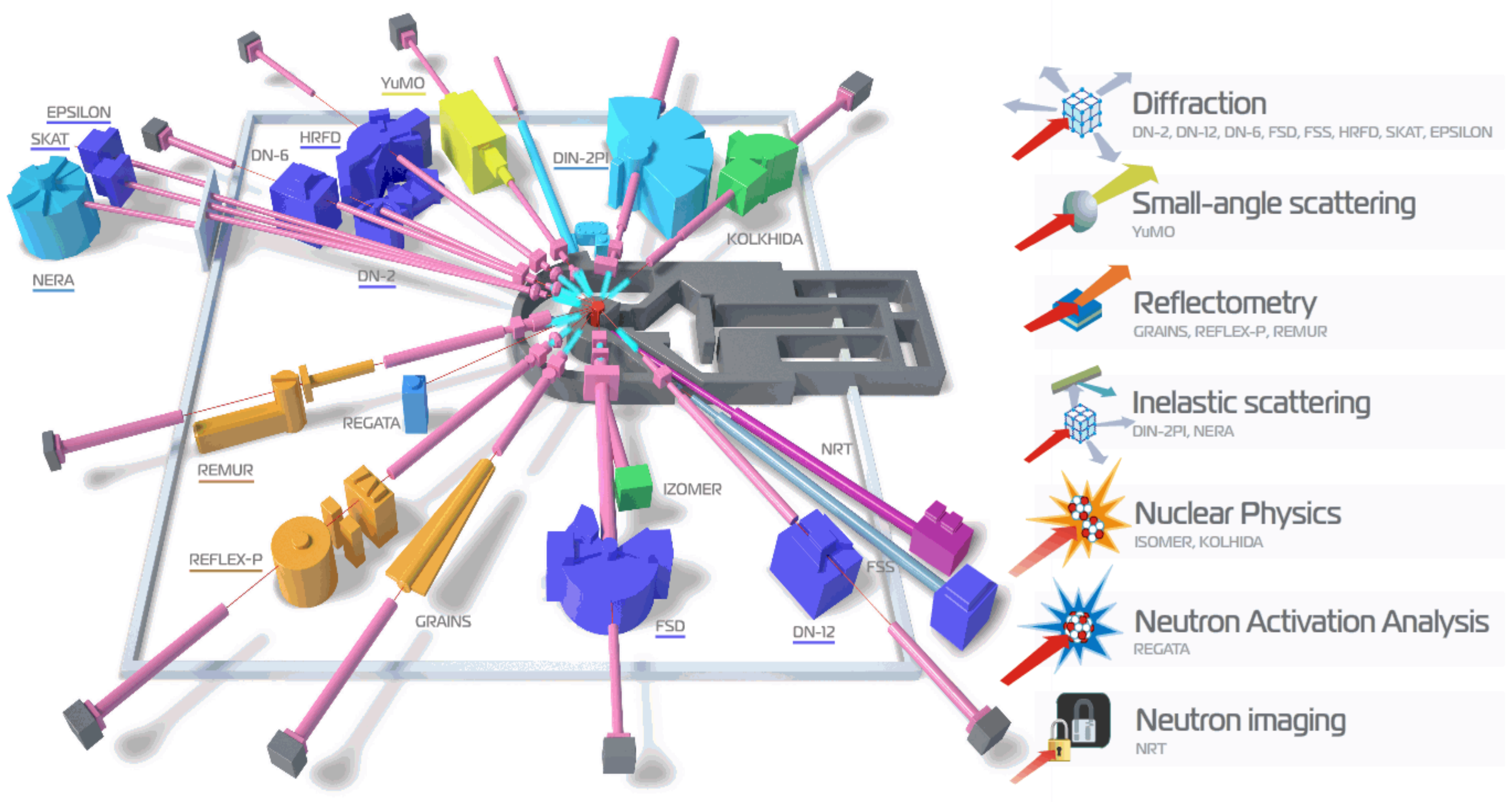
Cold neutrons
0 - 0.025 eV

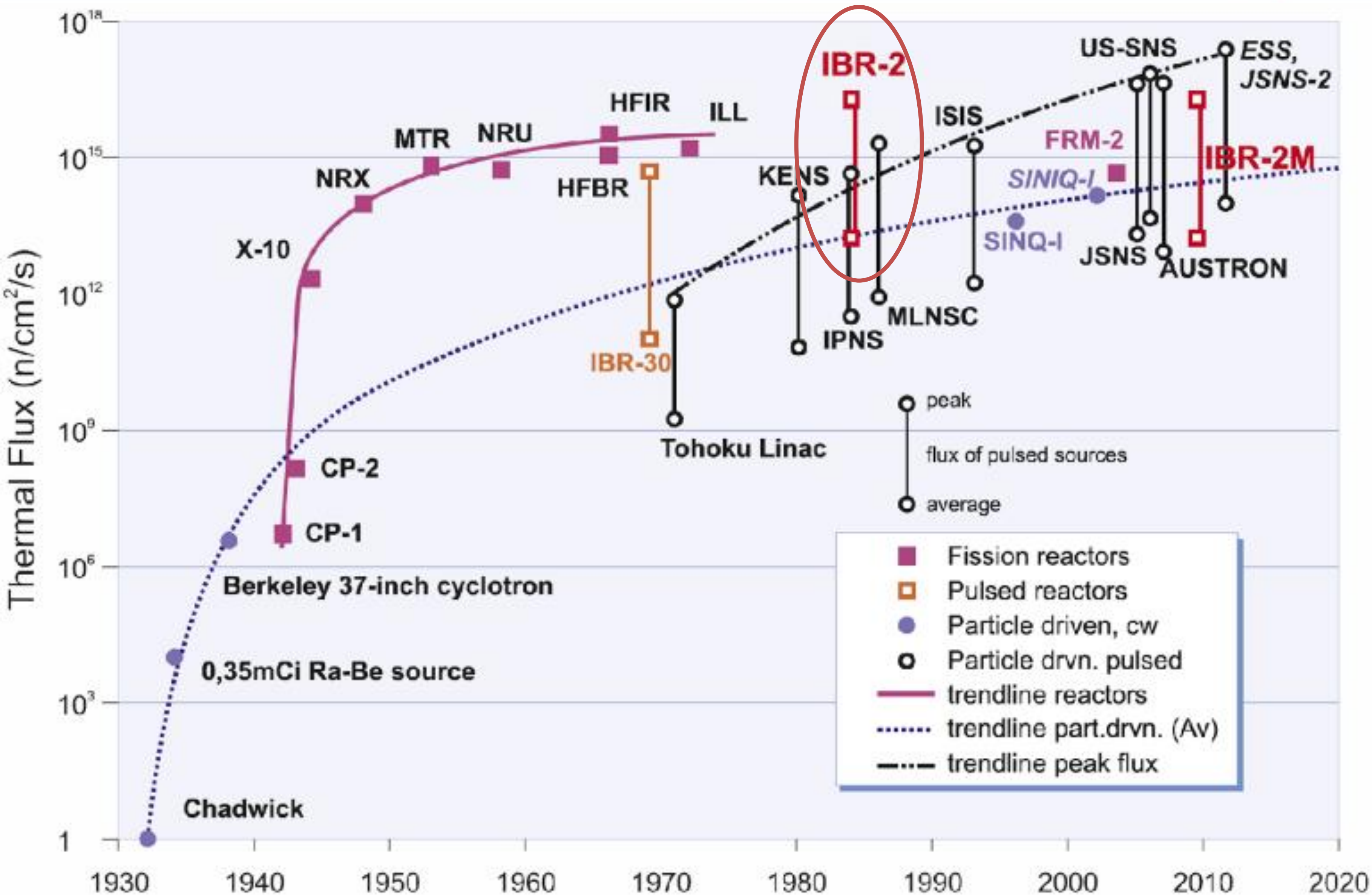




1. Main moveable reflector,
2. Auxillary moveable reflector,
3. Fuel assembly,
4. Stationary reflector,
5. **Cold moderators,**
6. Emergency system,
7. **Water moderators,**
8. Control rods;

# Suite of Spectrometers

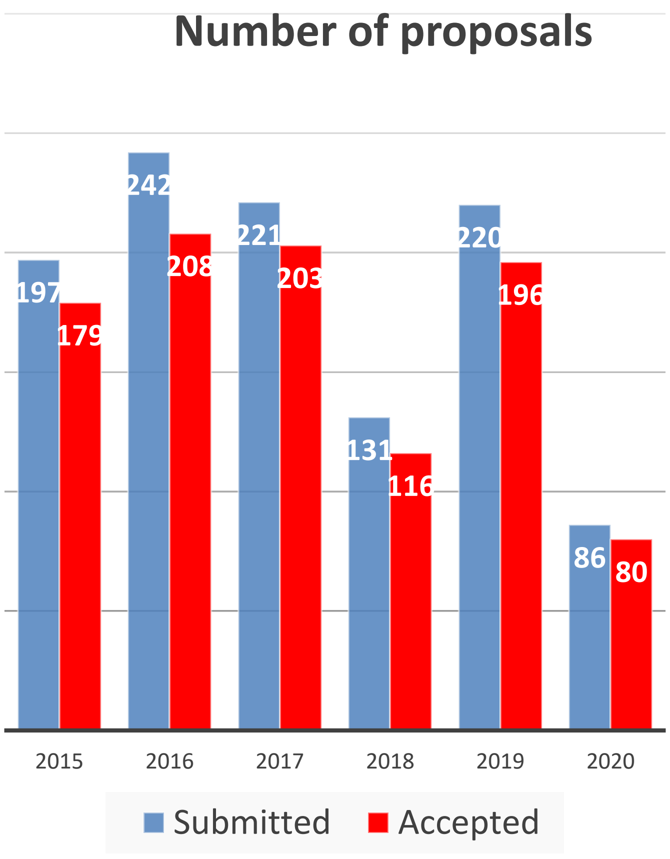
## Experimental facilities

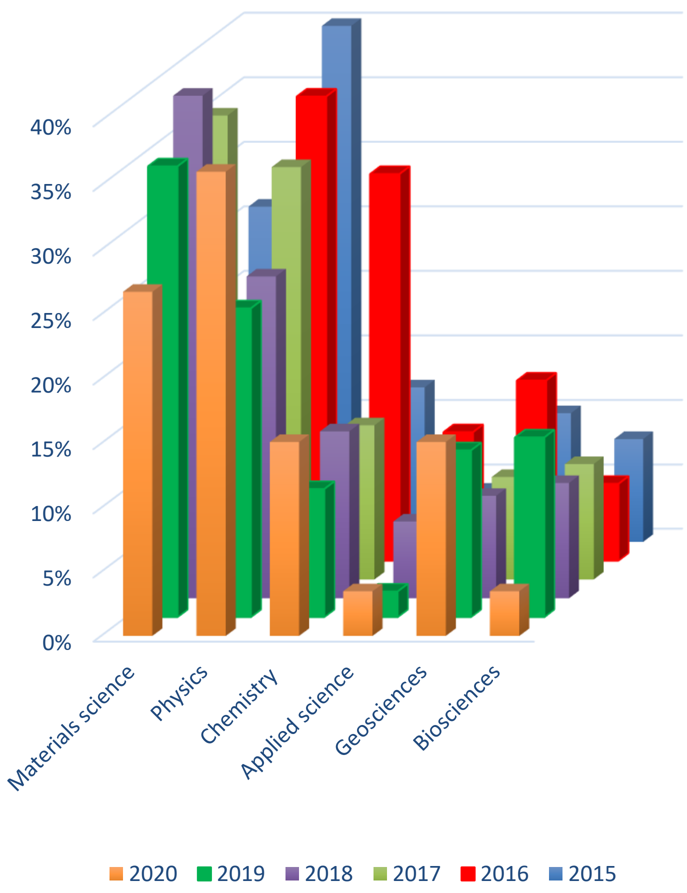



Thermal Flux (n/cm²/s)
10¹⁸
10¹⁵
10¹²
10⁹
10⁶
10³
1
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
IBR-2
US-SNS
ESS,
JSNS-2
HFIR
ILL
MTR
NRU
ISIS
FRM-2
IBR-2M
NRX
HFBR
KENS
SINQ-I
X-10
SINQ-I
JSNS
AUSTRON
MLNSC
IPNS
IBR-30
Tohoku Linac
peak
flux of pulsed sources
average
CP-2
CP-1
Berkeley 37-inch cyclotron
0,35mCi Ra-Be source
Chadwick
Fission reactors
Pulsed reactors
Particle driven, cw
Particle drvn. pulsed
trendline reactors
trendline part.drvn. (Av)
trendline peak flux

# User Program at IBR-2

**https://ibr-2.jinr.ru/**

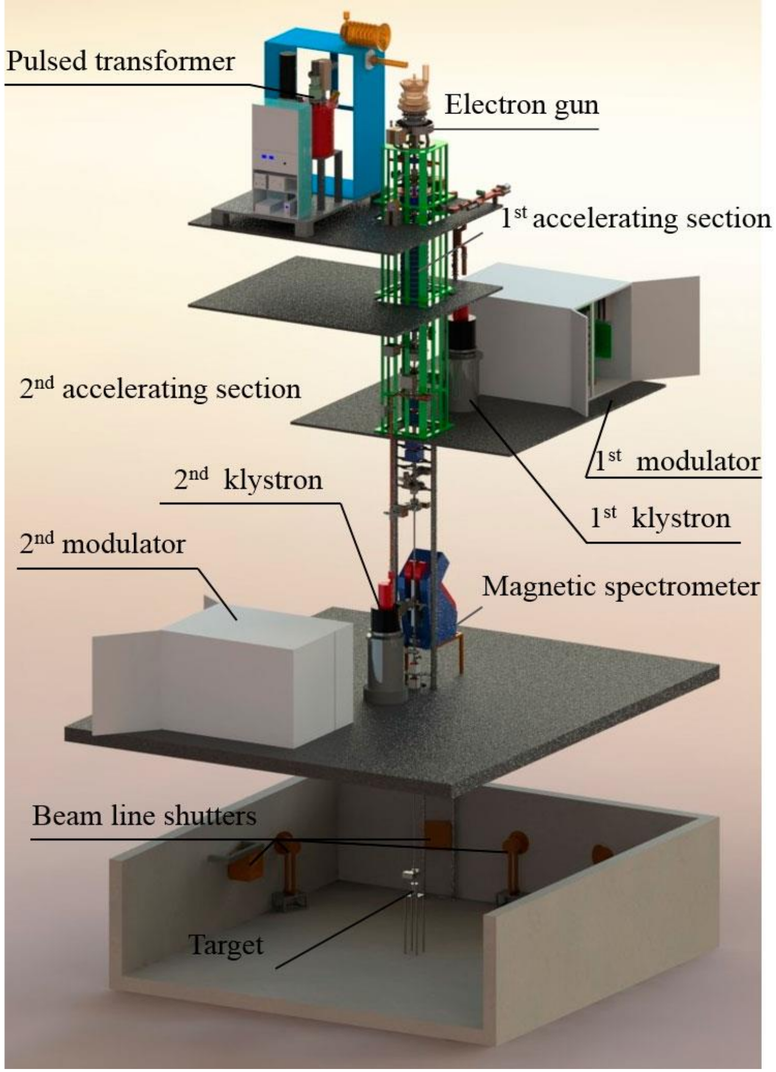


# Neutron source: IREN Facility (layout)

| Parameter | Project | I Stage | II Stage |
|---|---|---|---|
| Peak current (A) | 1.5 | 1.5–2.5 | 1.5–2.5 |
| Repetition rate (Hz) | 150 | 25 | 50 |
| Electron pulse duration (ns) | 250 | 100 | 100 |
| Electron energy (MeV) | 212 | 32–42 | 45–65 |
| Beam power (kW) | 12 | 0.1–0.4 | 0.3–1.2 |
| Neutron intensity (n/s) | $2 \times 10^{13}$ | $3 \times 10^{11}$ | $6 \times 10^{11}$ |

Quantum Beam Sci. 2017, 1, 6

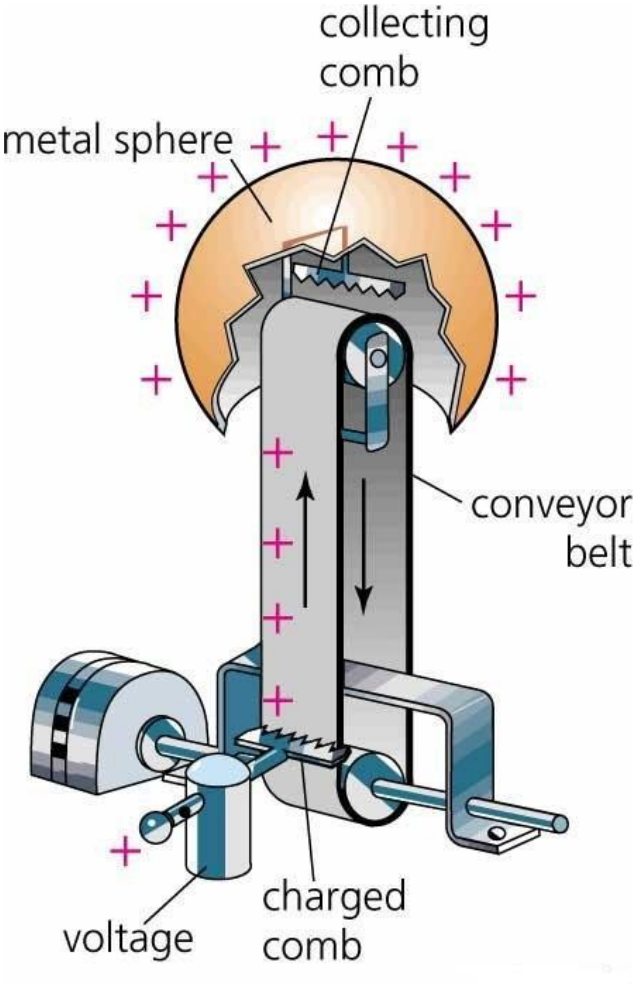



**Current IREN characteristics:**

- **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.**

**1200 hours/year**

# EG-5




**Electrostatic Van de Graaff accelerator, as one of main experimental facilities of Frank Laboratory of Neutron Physics was built in 1965.**

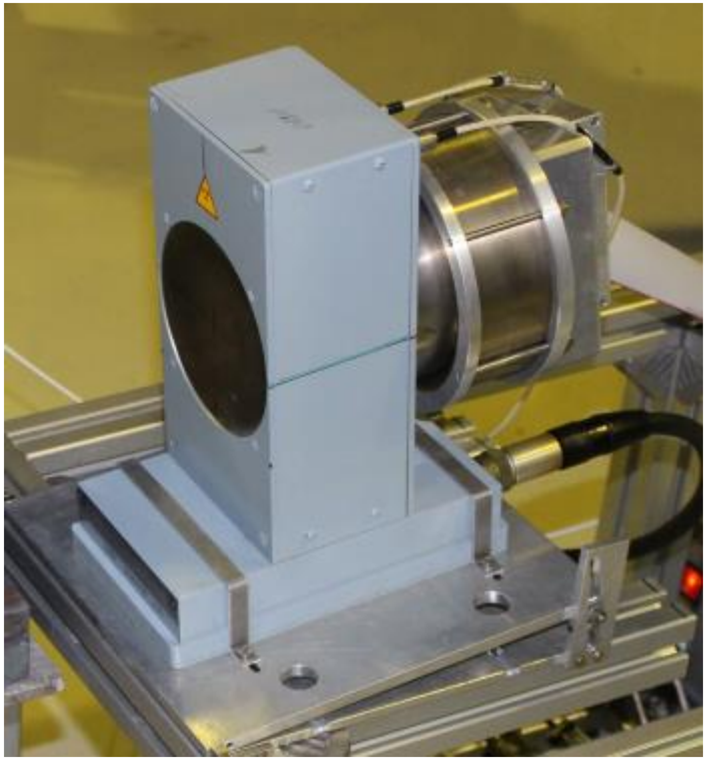
**The characteristics of EG-5 Accelerator:**
Energy region: 0.9 – 3.5 MeV
Beam intensity for $H$+: 30 μA
Beam intensity for $He$+: 10 μA
Energy spread < 500 eV
Number of beam lines: 6

**Neutrons can be produced by the reactions $d(d,n)^3He$, $d(t,n)^4He$, $^7Li(p,n)^7Be$**

**600 hours/year**

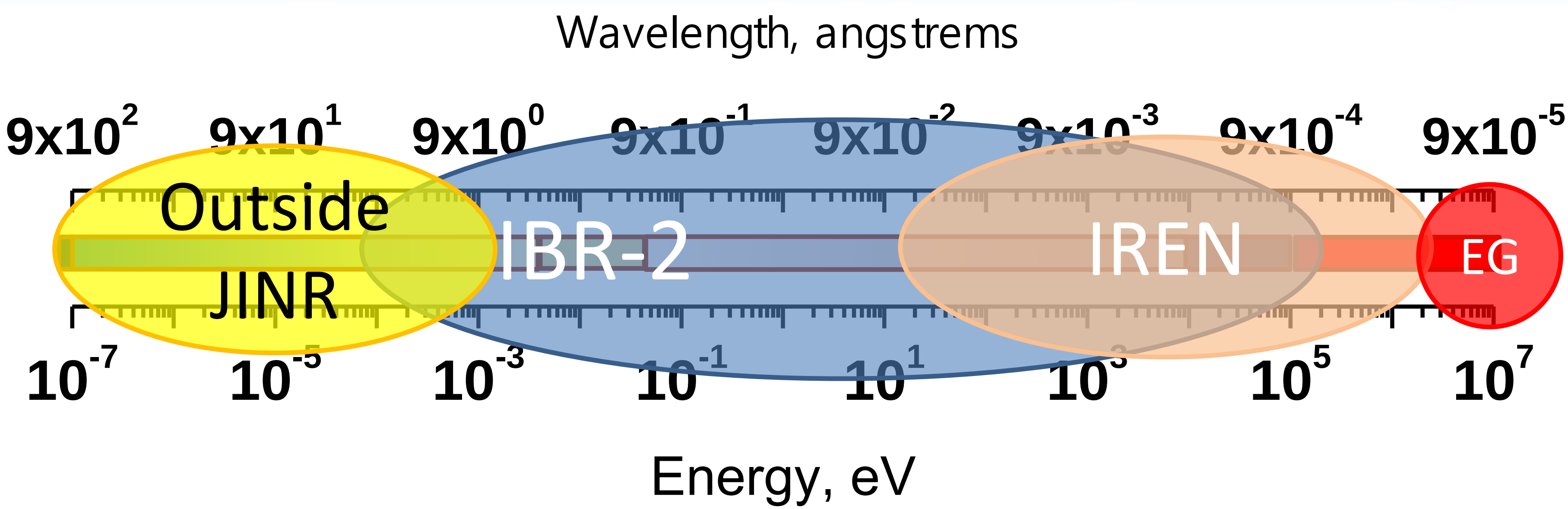
# Neutron generators

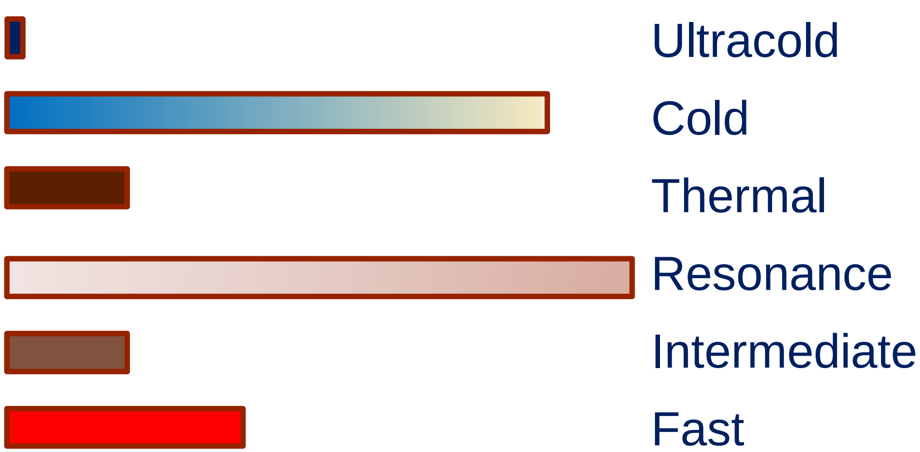
**DT/DD neutron generators of**
**14 MeV/2.5 MeV neutrons**
**Neutron yield up to $10^8$ $s^{-1}$**



# Neutron radioisotope sources

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




| Neutron energy | Energy range |
| --- | --- |
| 0.0-0.025 eV | Cold |
| 0.025 eV | Thermal |
| 10-300eV | Resonance |
| 300 eV-1MeV | Intermediate |
| 1-20MeV | Fast |

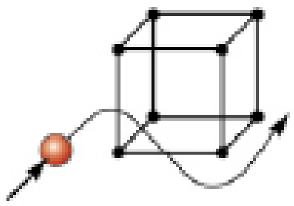
# Two scientific directions:

- Condensed matter physics

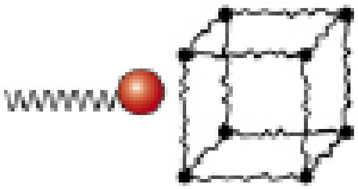
- Nuclear physics with neutrons

# Condensed matter physics at IBR-2
# Why neutrons?

✌Thermal neutrons **wavelength** is close to characteristic interatomic distances in crystals (~2 A):
**good for structural investigations**.

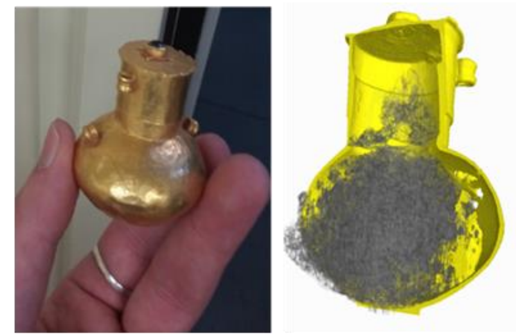


✌ Thermal neutrons **energy** is close to characteristic energies of atomic excitations (~0.02 eV):
**good for lattice dynamics investigations.**

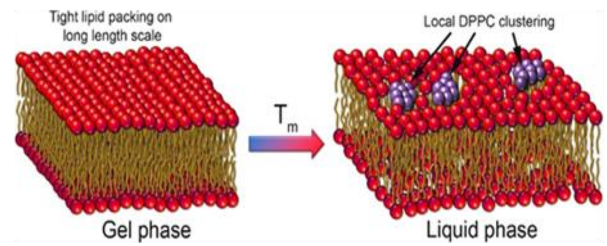


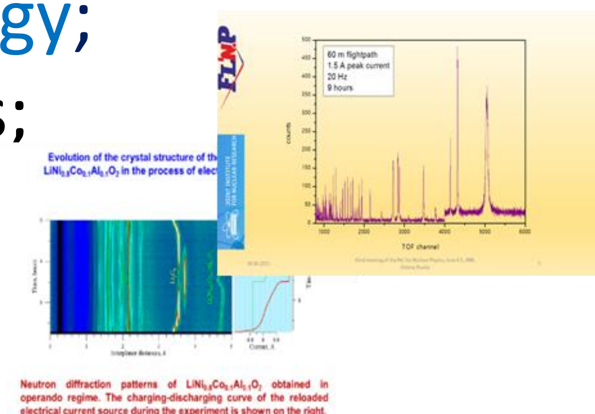
✌ Neutrons have a **magnetic momentum**:
**good for investigation of magnetic structures and phenomena**.

# Condensed matter physics at IBR-2



- Physics and Chemistry of Novel Functional Materials;
- Physics of Nanosystems and Nanoscale Phenomena;
- Physics and Chemistry of Complex Liquids and Polymers;
- Molecular Biology and Pharmacology;
- Materials and Engineering Sciences;
- Neutron Radiography and Tomography;



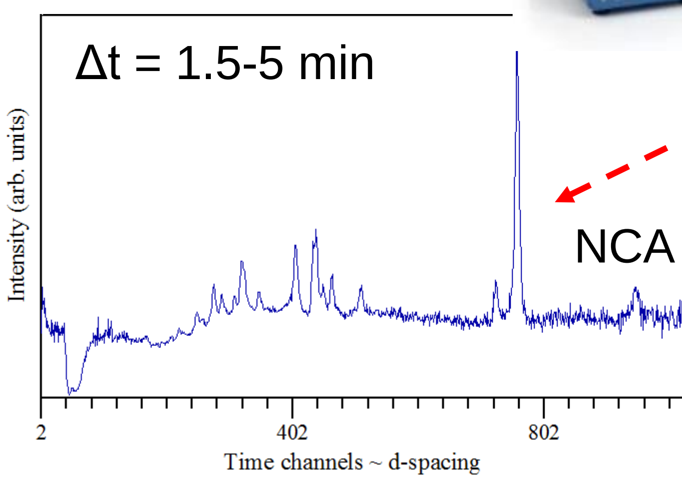



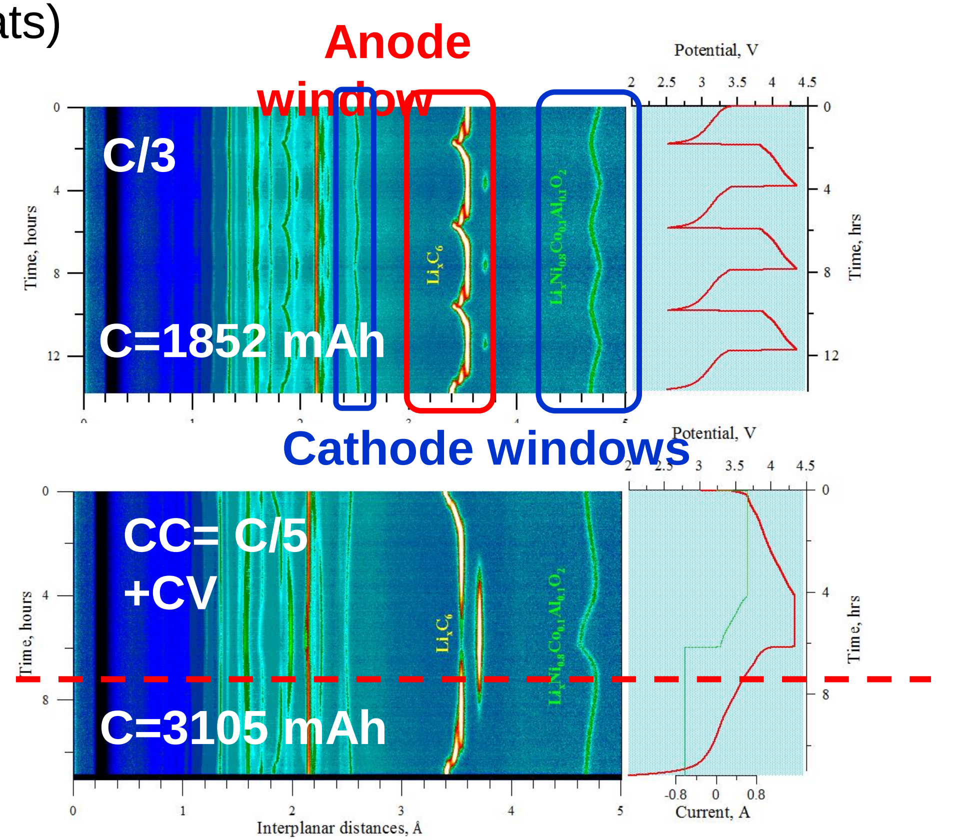
# *Operando* neutron diffraction study of Li-ion power sources

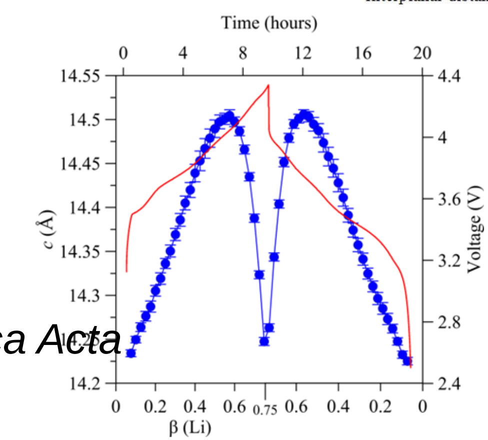
U=2.5-4.33 V (Elins / Biologic potentiostats)

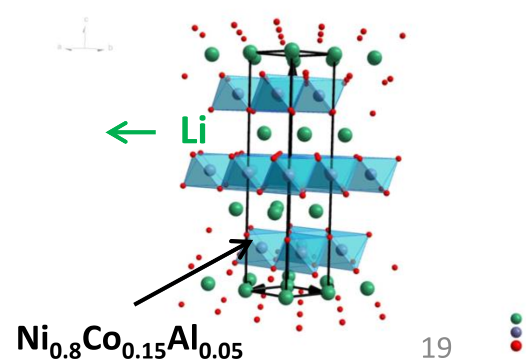
C=3100 mAh, Cт=278.9 mAh/g

$m_{cathode}$=14.6 g

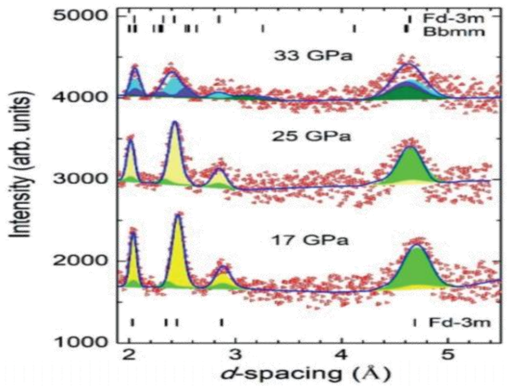

Bobrikov, Samoylova, Sumnikov et al.

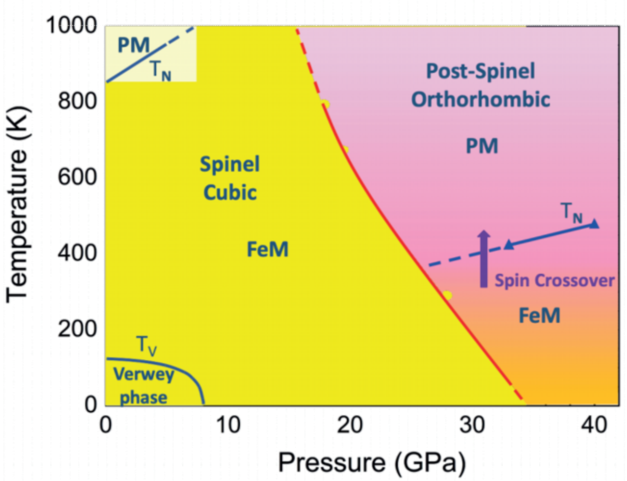
*Journal of Power Sources, Electrochimica Acta*

(2017-2018)

# Magnetism and Magnetic Materials

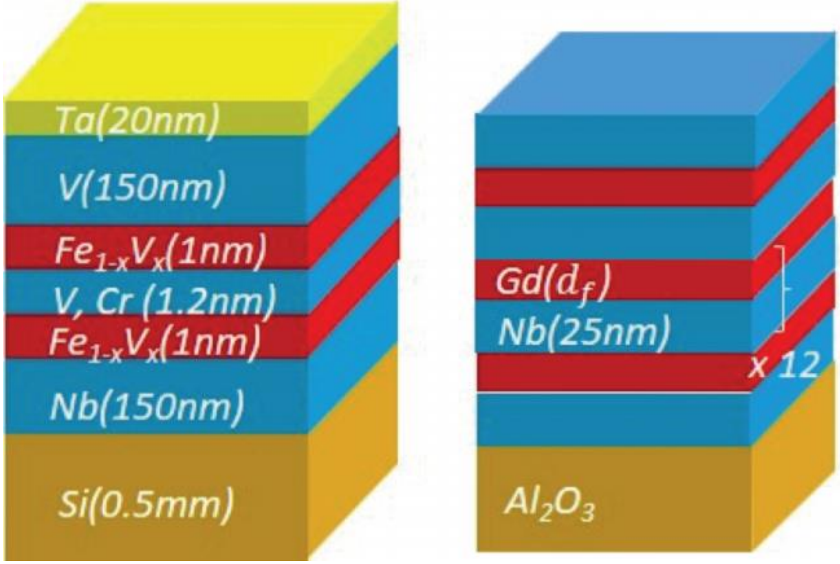
- Word magnetism comes from **Magnetite**
- **Neutron diffraction** reveals crystal and magnetic structure at **high pressure**




D.P. Kozlenko et al., Sci Rep 9, 4464 (2019)

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



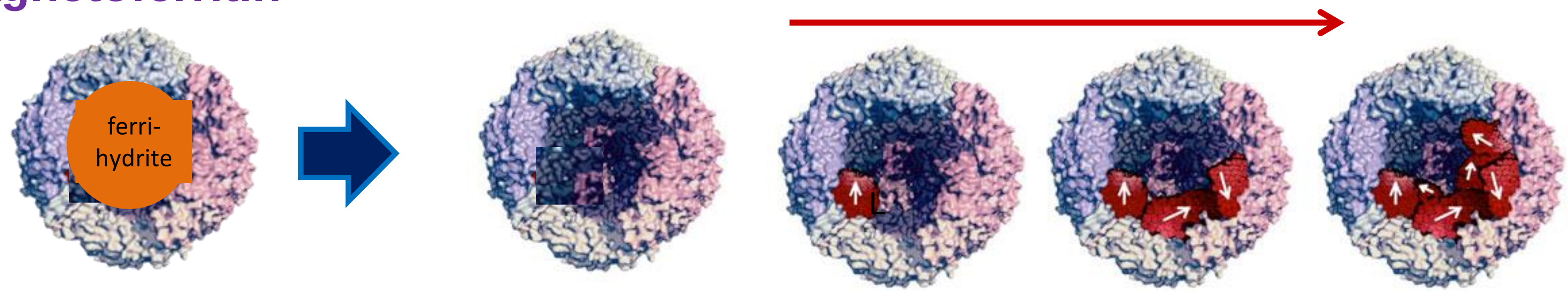

- **Magnetic thin films** with a layered structure open up new opportunities
- Spintronics, magnetic memory devices, quantum computing, superconducting spin valves, polarized electron injectors

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

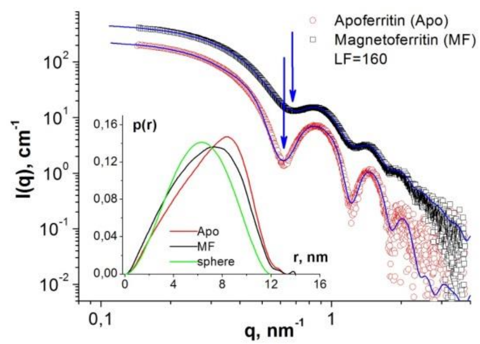
# Interactions of Nanoparticles with Bio-Macromolecules

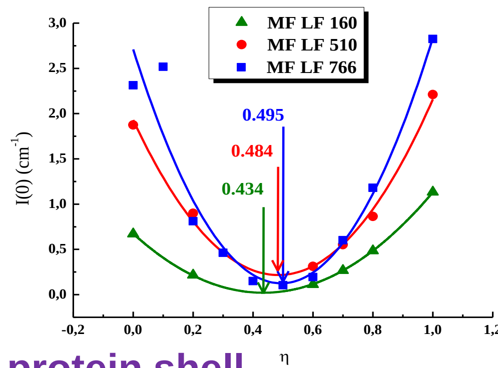
## Magnetoferritin

**Loading factor (LF)**

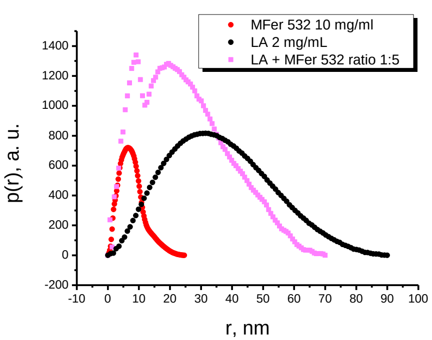



Small Angle Neutron Scattering suggests a partial disassembling of the appoferritin shell due to the increasing content of the magnetic (iron oxides) material




**Instability of protein shell**




**Destroy of amyloids**

SAXS experiments indicate the destroying effect of Mfer on lysozyme amyloid fibrils with the effect increasing with the loading factor.

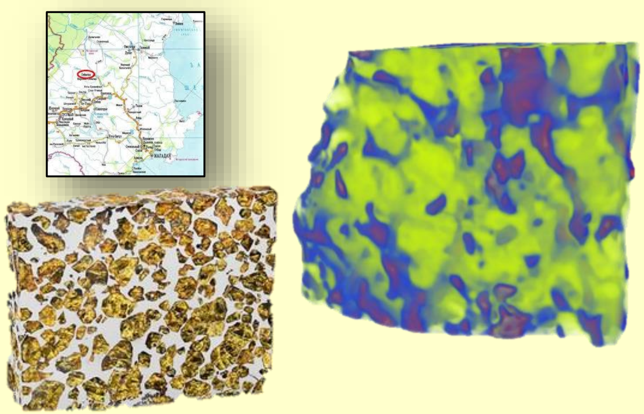


L. Melníková, V.I. Petrenko, M.V. Avdeev, et al. Colloids and Surfaces B 123 (2014)
P.Kopcansky, K.Siposova, L.Melnikova, et al. J of Magnetism and Magnetic Materials 377 (2015)

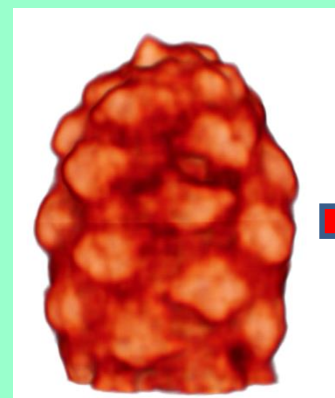
# Development of Neutron Imaging Techniques

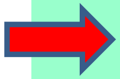
## Radiography

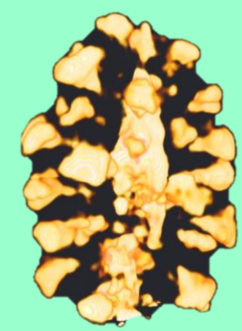
## Tomography



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







3D reconstruction of internal structure of Protosequoia cone (cretaceous period) from Paleontological Institute RAS



courtesy of Dr. D.P. Kozlenko

# Neutron Radiography and Tomography

Tver treasure found in 2014

Archaeology Institute of
the Russian Academy of Science

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

# Main activities in the field of nuclear physics with neutrons:

1. **Investigations of the neutron induced nuclear reactions:**
   - fundamental symmetries;
   - highly excited states of the nuclei;
   - nuclear fission;
   - nuclear data.
2. **Investigations of the fundamental properties of the neutron, ultra-cold neutrons:**
   - tests of quantum mechanics;
   - search for new type of interactions;
   - neutron lifetime measurement.
3. **Applied and methodological research:**
   - neutron activation analysis;
   - neutron in space;
   - Ion beam analysis:

# Neutron source: IREN Facility (layout)

| Parameter | Project | I Stage | II Stage |
|---|---|---|---|
| Peak current (A) | 1.5 | 1.5–2.5 | 1.5–2.5 |
| Repetition rate (Hz) | 150 | 25 | 50 |
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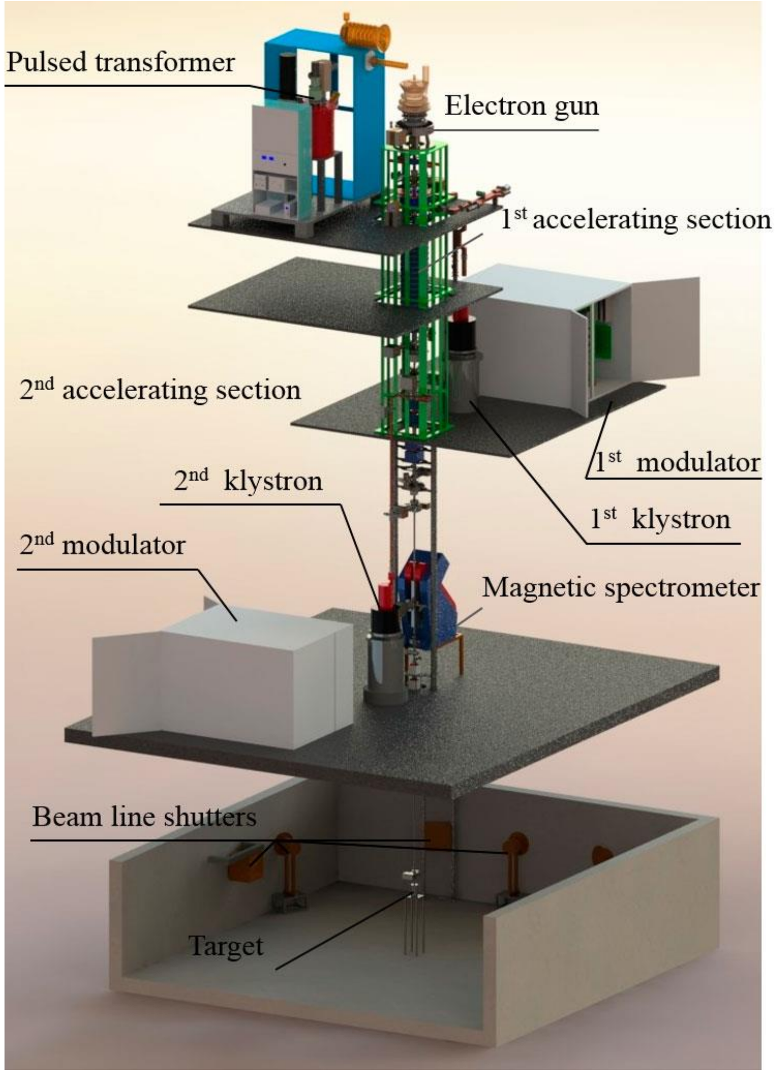
Quantum Beam Sci. 2017, 1, 6

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- **electron energy – 120 MeV**
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- **repetition rate – 25/50 Hz**
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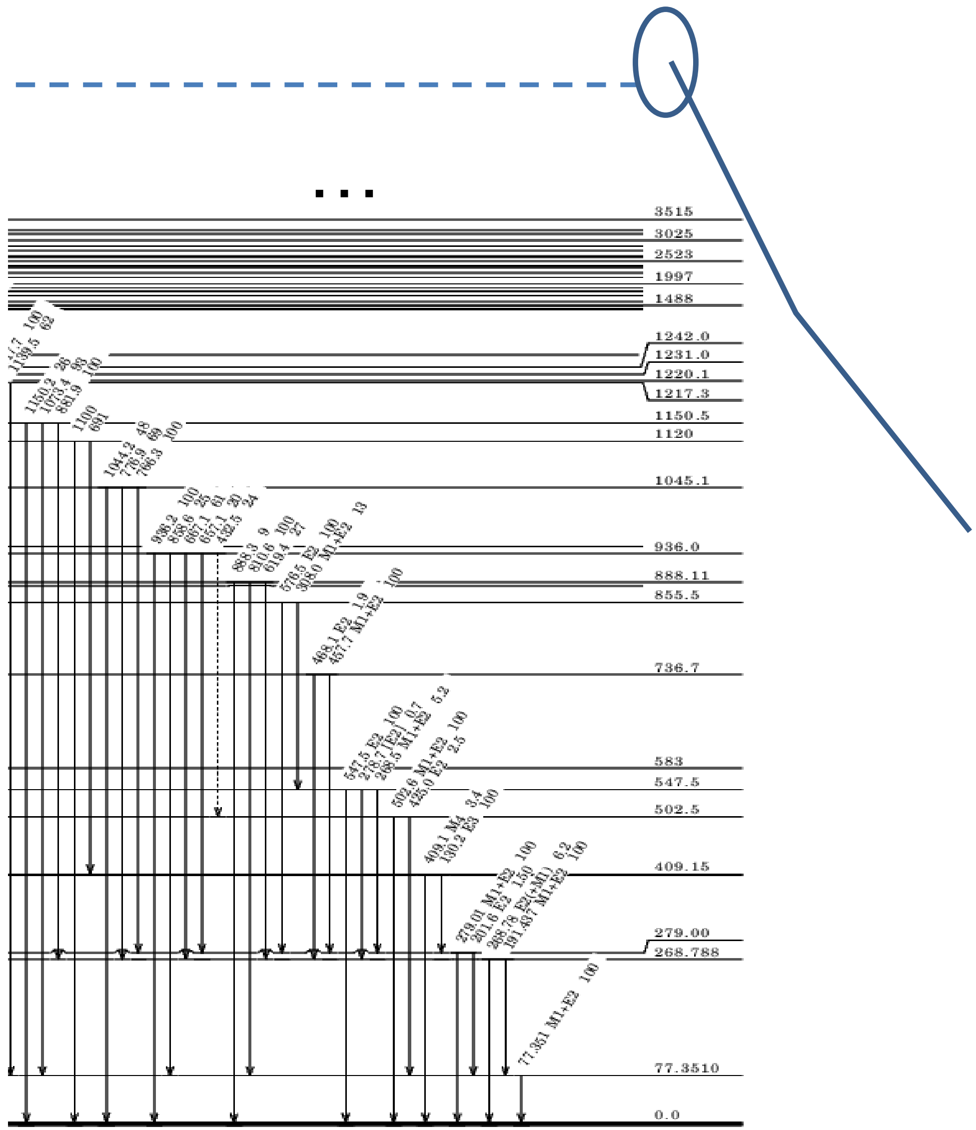
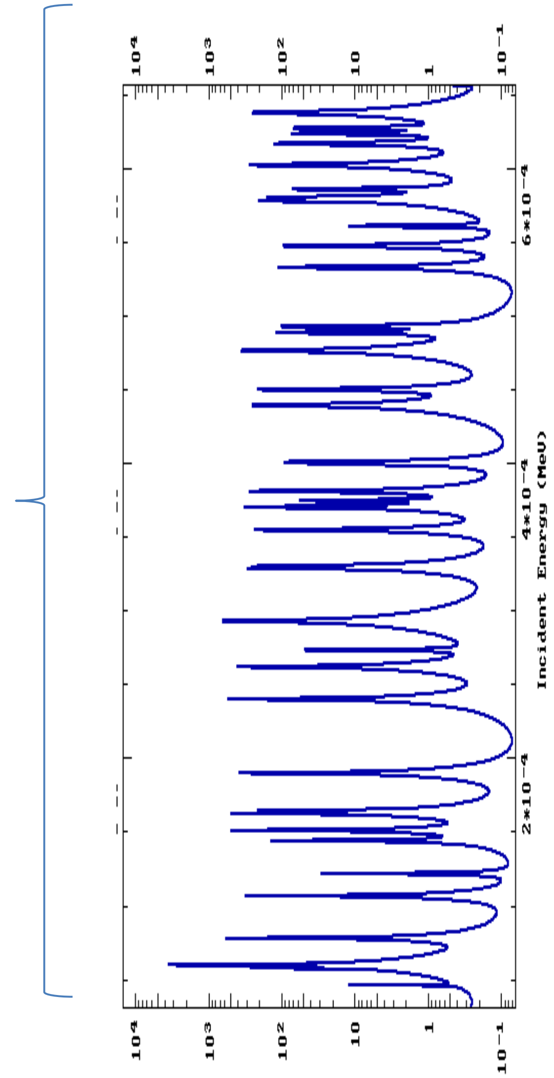
**1200 hours/year**

# Neutron resonances

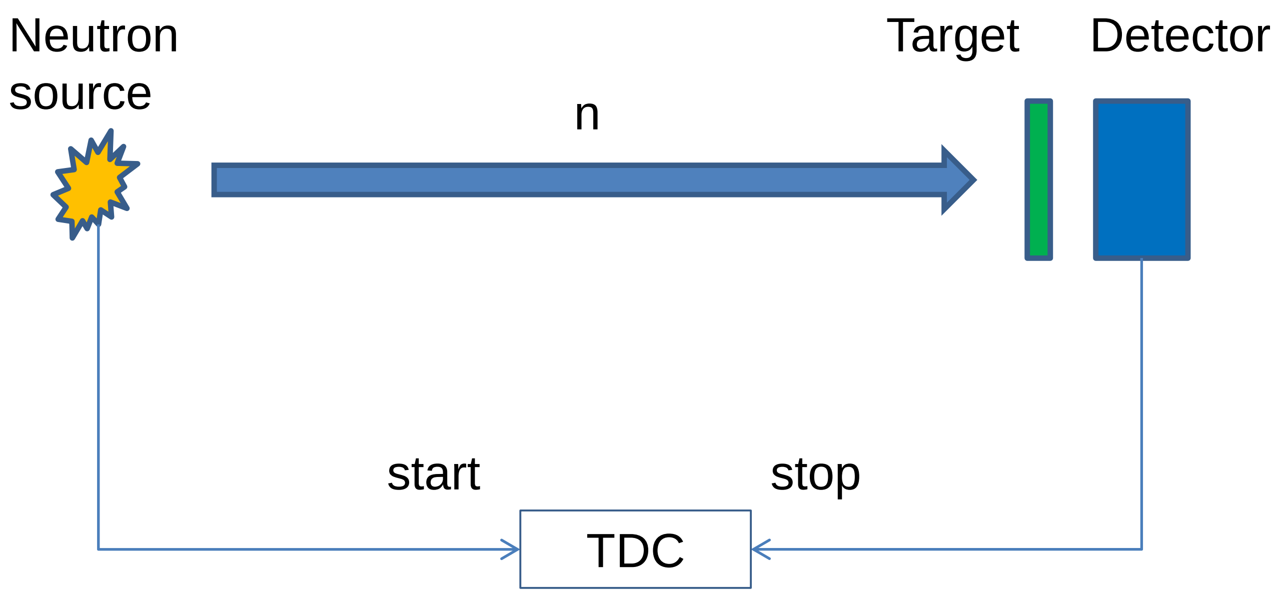
$^{197}Au + n \rightarrow {}^{198}Au^*$ Nucleus + neutron

$B_n$



# Neutron time-of-flight measurements

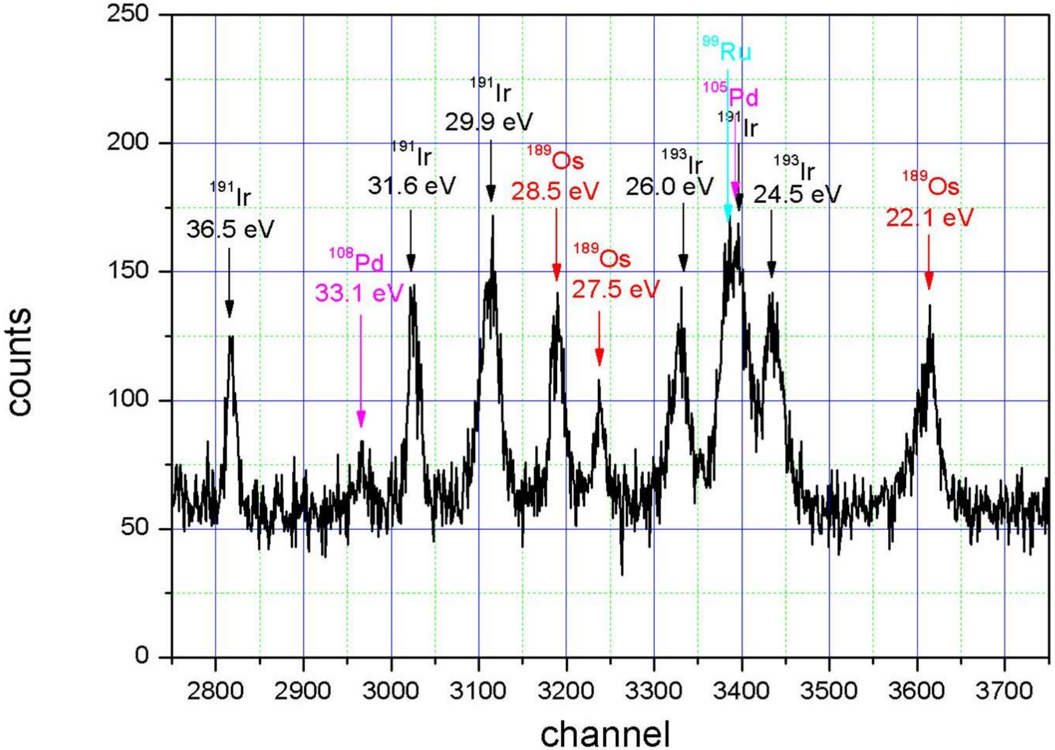



$$E = \frac{mL^2}{2t^2}$$

For the neutron

$$E = \frac{72.3L^2}{t^2}$$

# Experiments at IREN: Non-destructive analysis of the geological samples




| Element | Mass of the element in the sample (g) |
|---|---|
| Pt | 2.7±0.3 |
| Pd | 0.1±0.02 |
| Ir | 5.2±0.6 |
| Ru | 1.14±0.2 |
| Os | 4.3±0.5 |

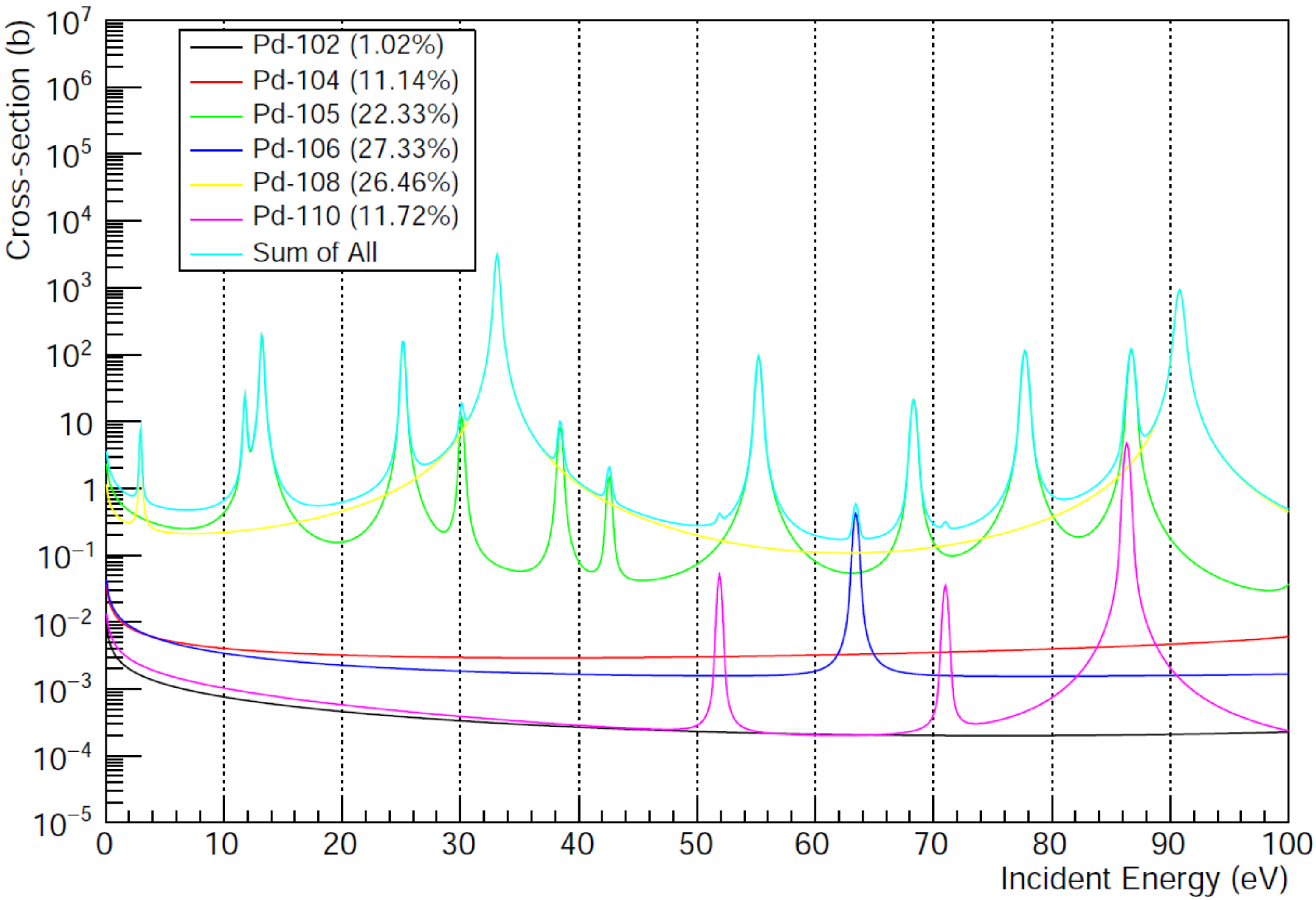
## Advantages

- fully nondestructive
- bulk investigation
- negligible residual activity
- sensitivity to the isotopic composition
- possibility to investigate radioactive samples

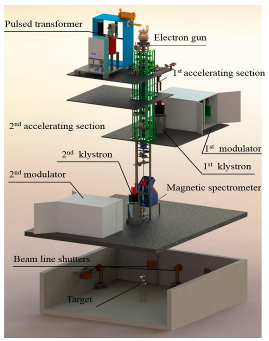
# The use of resonance neutron method for investigating parts of the “Proton” rocket engine

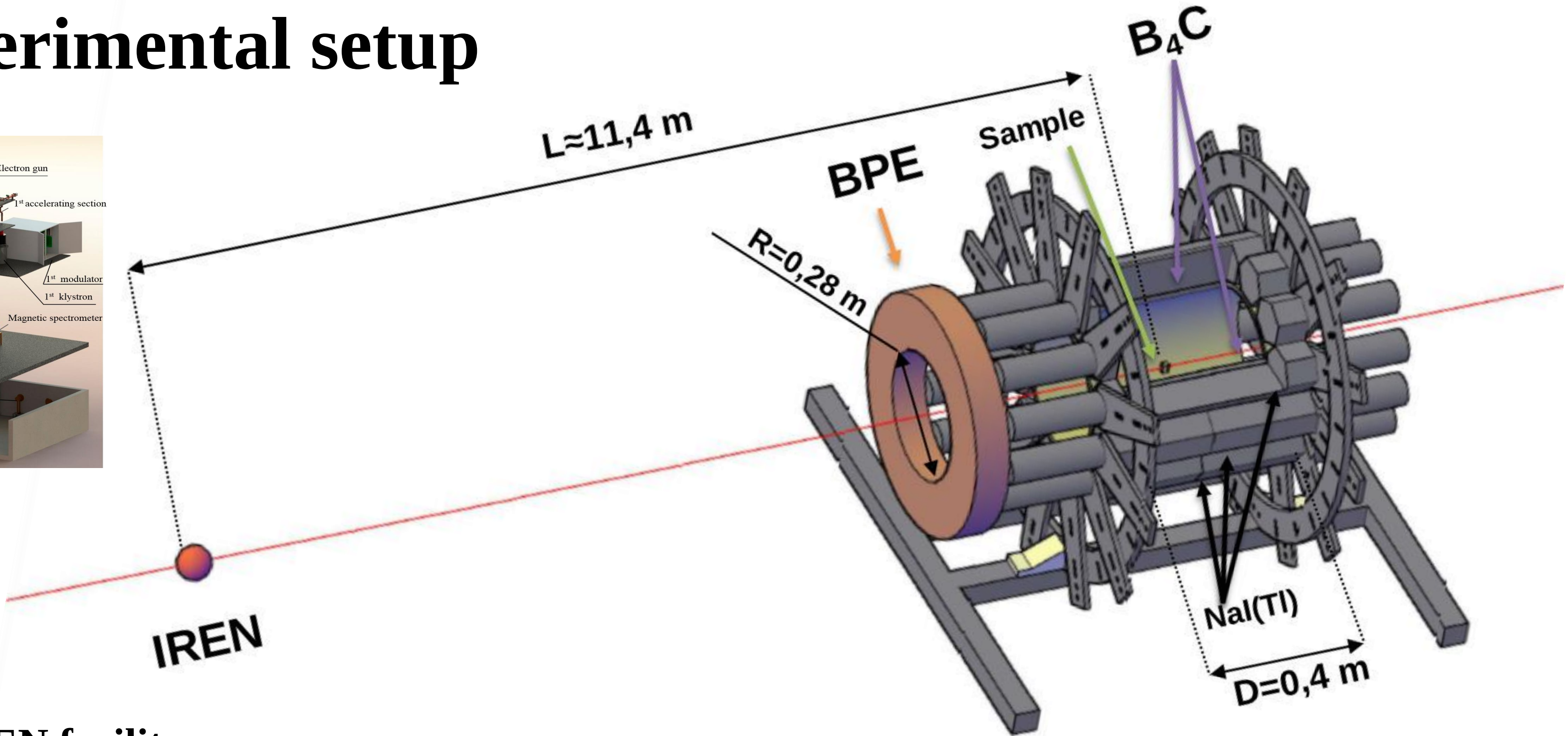

**One hypothesis for crash of the Proton rocket is presence of palladium in some critical components of the engine**

# Resonances in Pd isotopes (ENDF/B-VII.1)

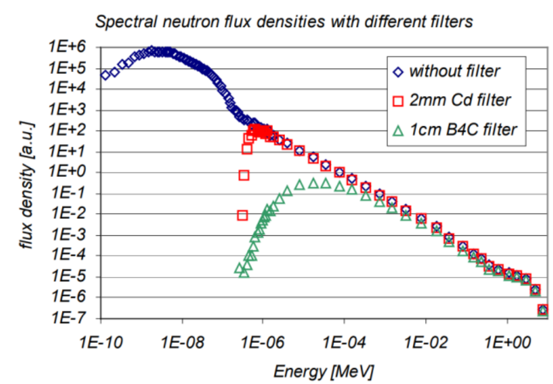


# Experimental setup

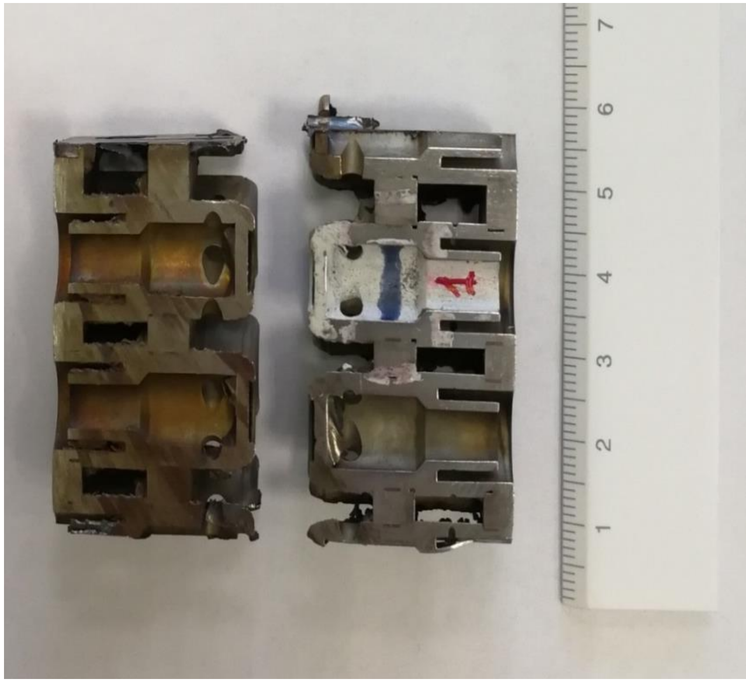


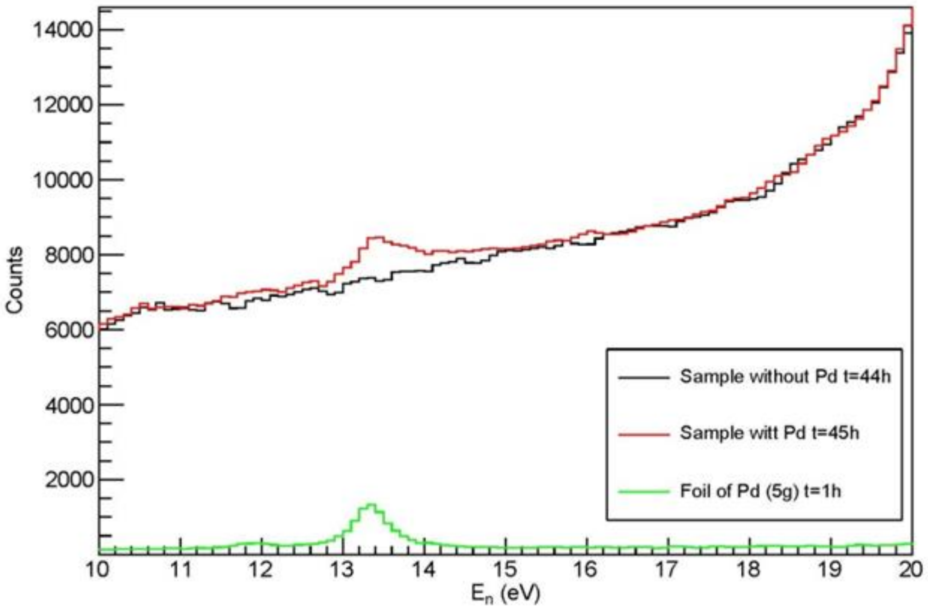




- **IREN facility**
- **“Romashka” gamma-spectrometer: 24 hexagonal NaI(Tl) crystals (78x90x200 mm)**
- **10cm-thick Boron polyethylene (BPE) collimator**
- **$B_4C$ powder of 1cm thickness (ρ=1.8 g/cm3), encapsulated in-between 2 Al cylinders of 0.5 mm wall thickness, was used to capture the neutrons scattered by the sample**
- **Samples (in the center of “Romashka” system)**



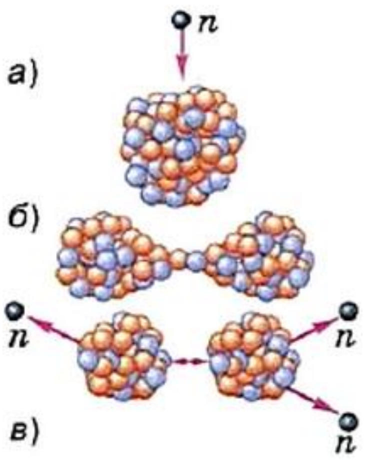
# The results

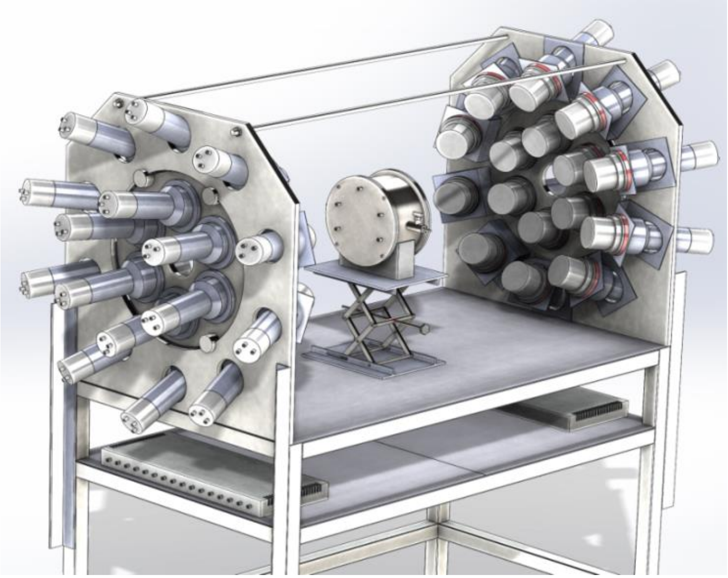


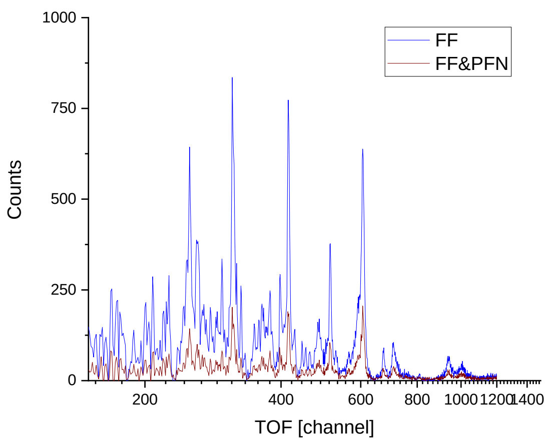

**The amount of Pd in the ~60 g sample was found to be 98 ± 10 mg.**

# Nuclear fission studies

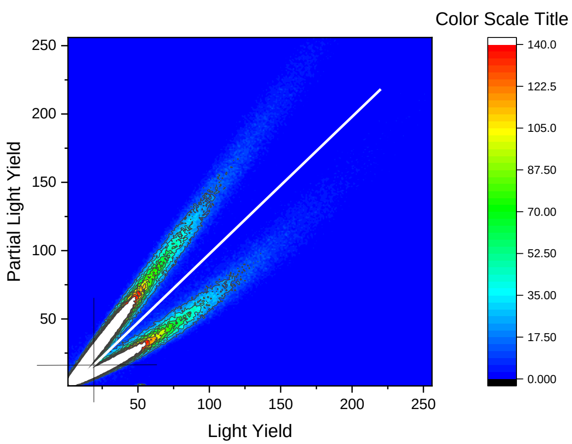


**Experimental setup consisting of a double ionization chamber and 32 neutron detectors based on B501 liquid scintillator**

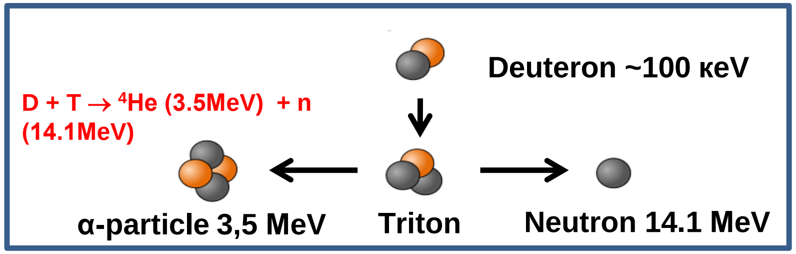



**TOFspectra with and without neutron detection**

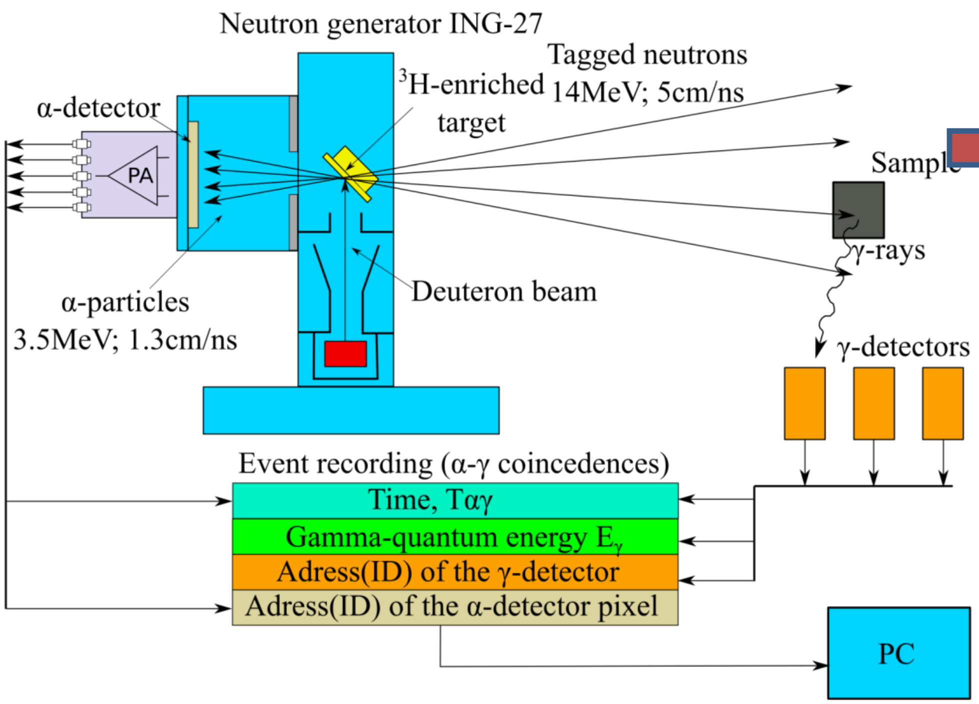


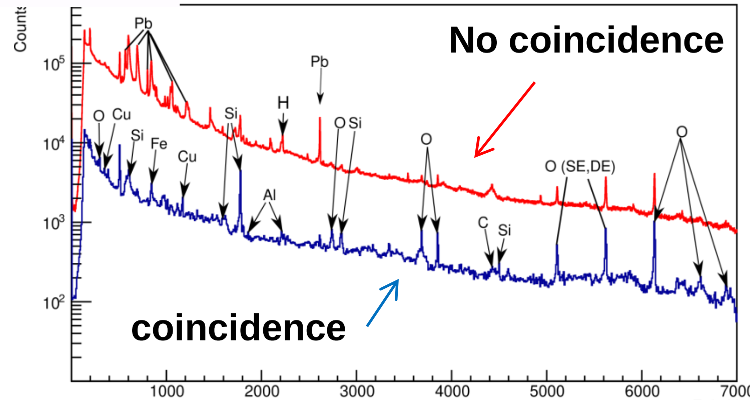

**Neutron-gamma separation plot**

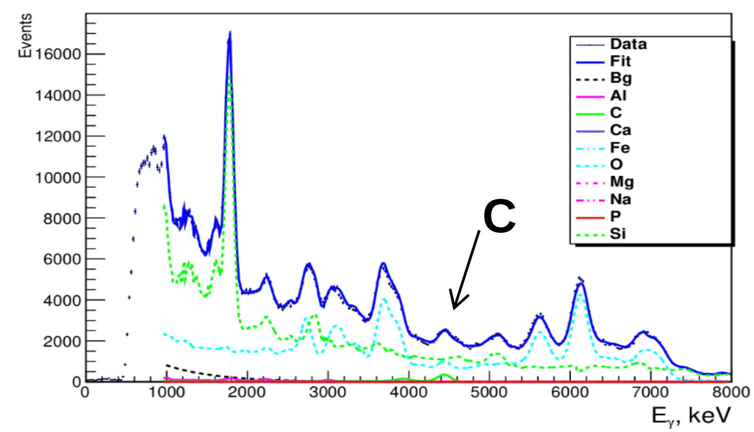
# Project TANGRA: using tagged neutron method




Neutron generator ING-27



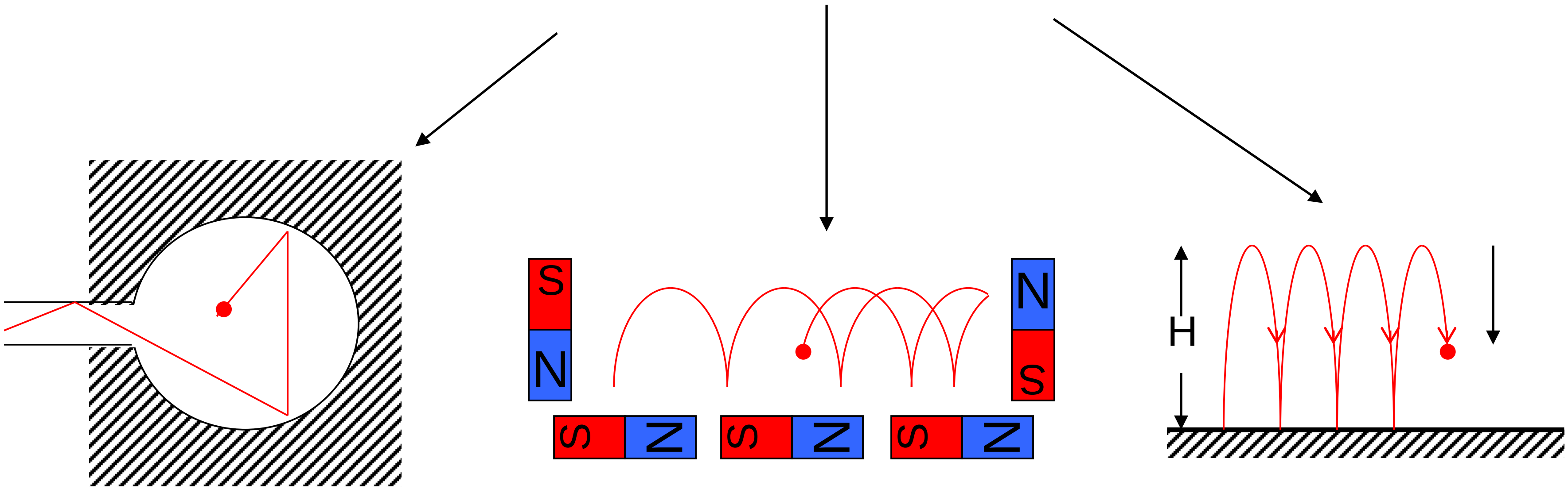




**Elements can be identified by their characteristic spectra.**

# Ultracold neutrons (UCN)

## Potential of interaction of slow neutrons with matter :



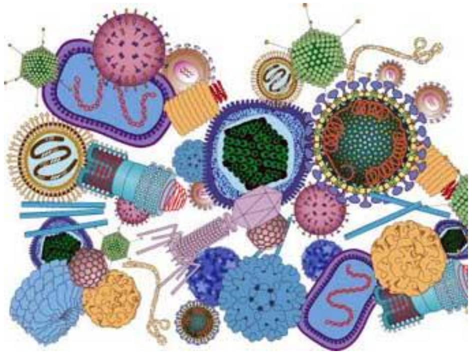

| | |
|---|---|
| Effective potential | ~ **$10^{-7}$ eV** |
| Gravity: | ~ **$10^{-7}$ eV** / Meter |
| Magnetic field: | ~ **$10^{-7}$ eV** / Tesla |

# UCN parameters

$V \leq 5$ m/c  20 km/h

You might overtake them by bike

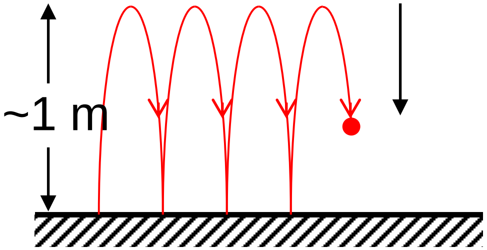
$\lambda \geq 500$ Å  50 nm



Typical dimensions of viruses

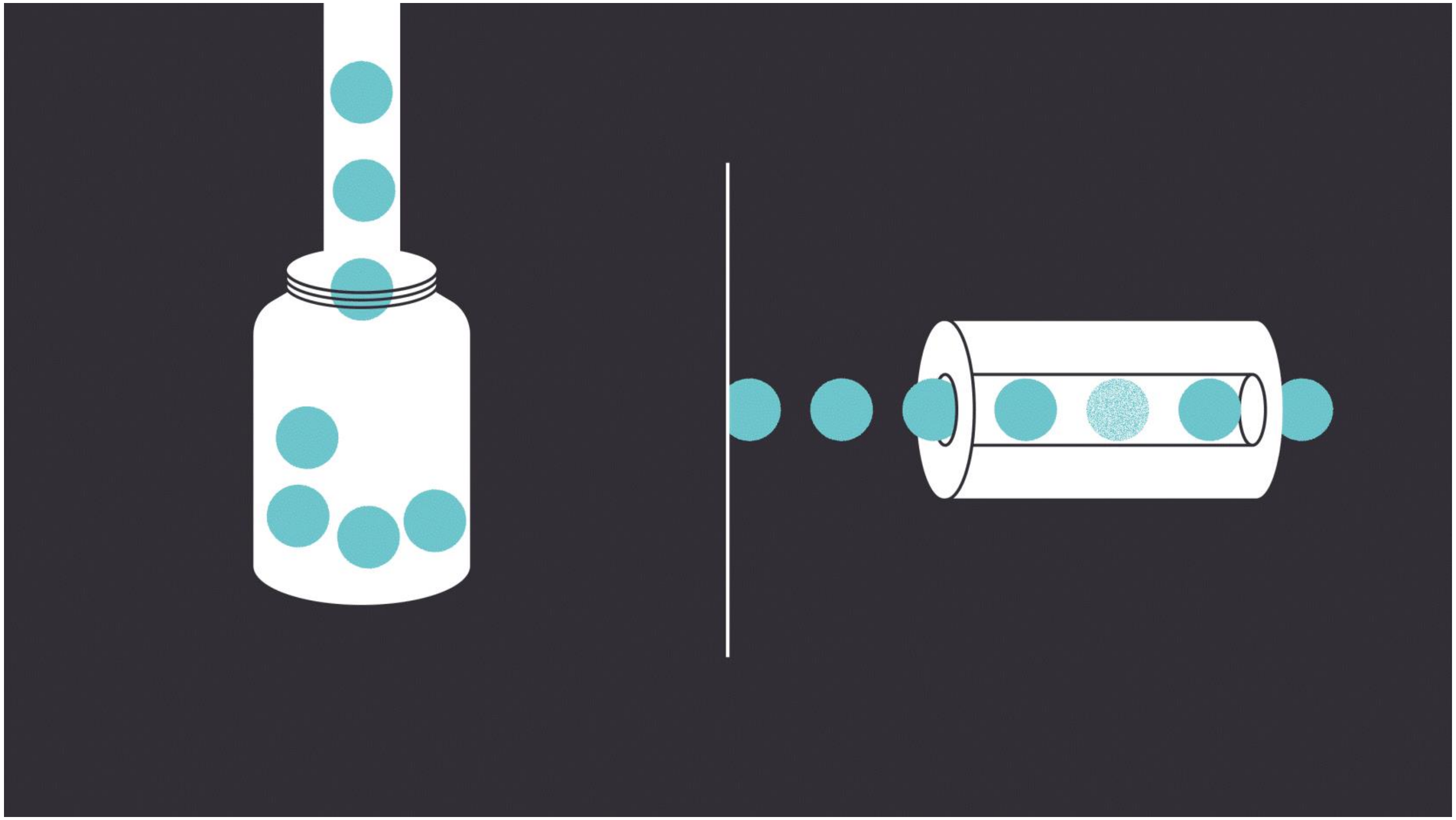
$E \leq 10^{-7}$ eV

$T \leq 10^{-3}$ K




1 cm ~1.02·neV

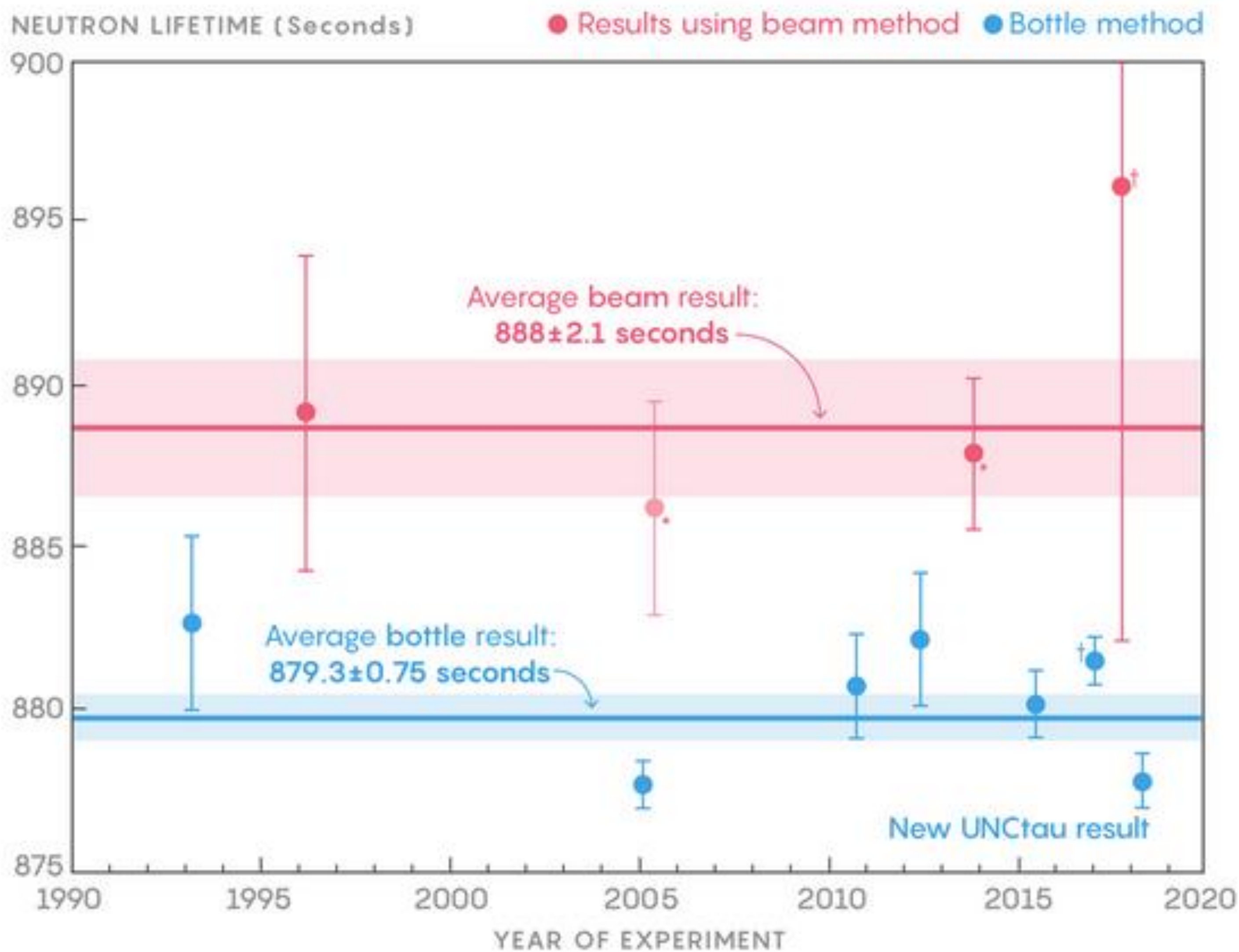
# Measurements of the neutron lifetime $\tau_n$



Storage experiments with UCN

Beam experiments with cold neutrons

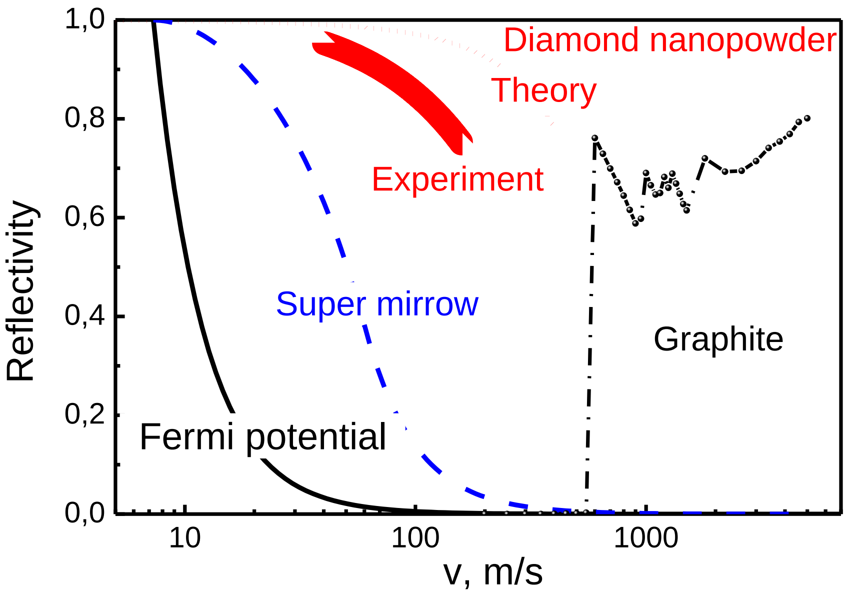
# Neutron Lifetime Puzzle



# 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:

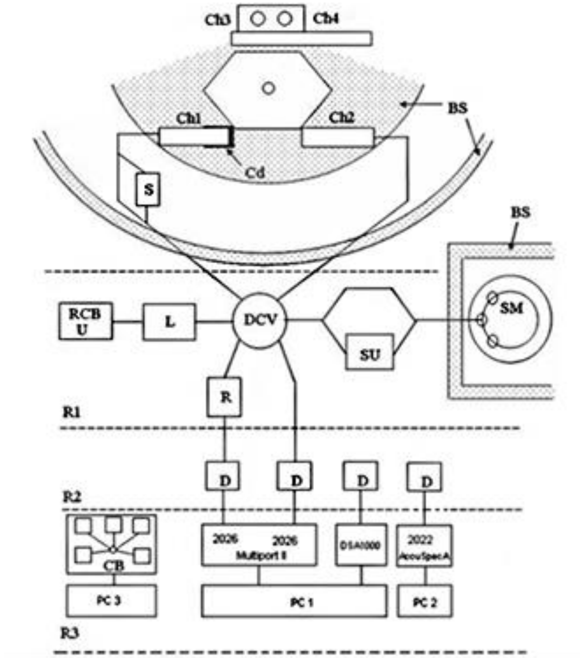
- Storage of very cold neutrons

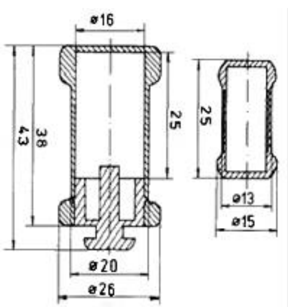
  dozens of times possible increasing neutron density

- Using as reflector in cold neutron souse

  dozens of times more intensive VCN and UCN source

# Neutron Activation Analysis facility REGATA

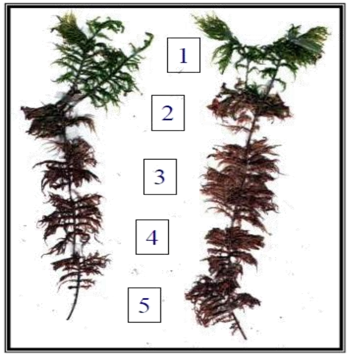



**http://flnp-naa.jinr.ru/**

## 1993: Biomonitoring…

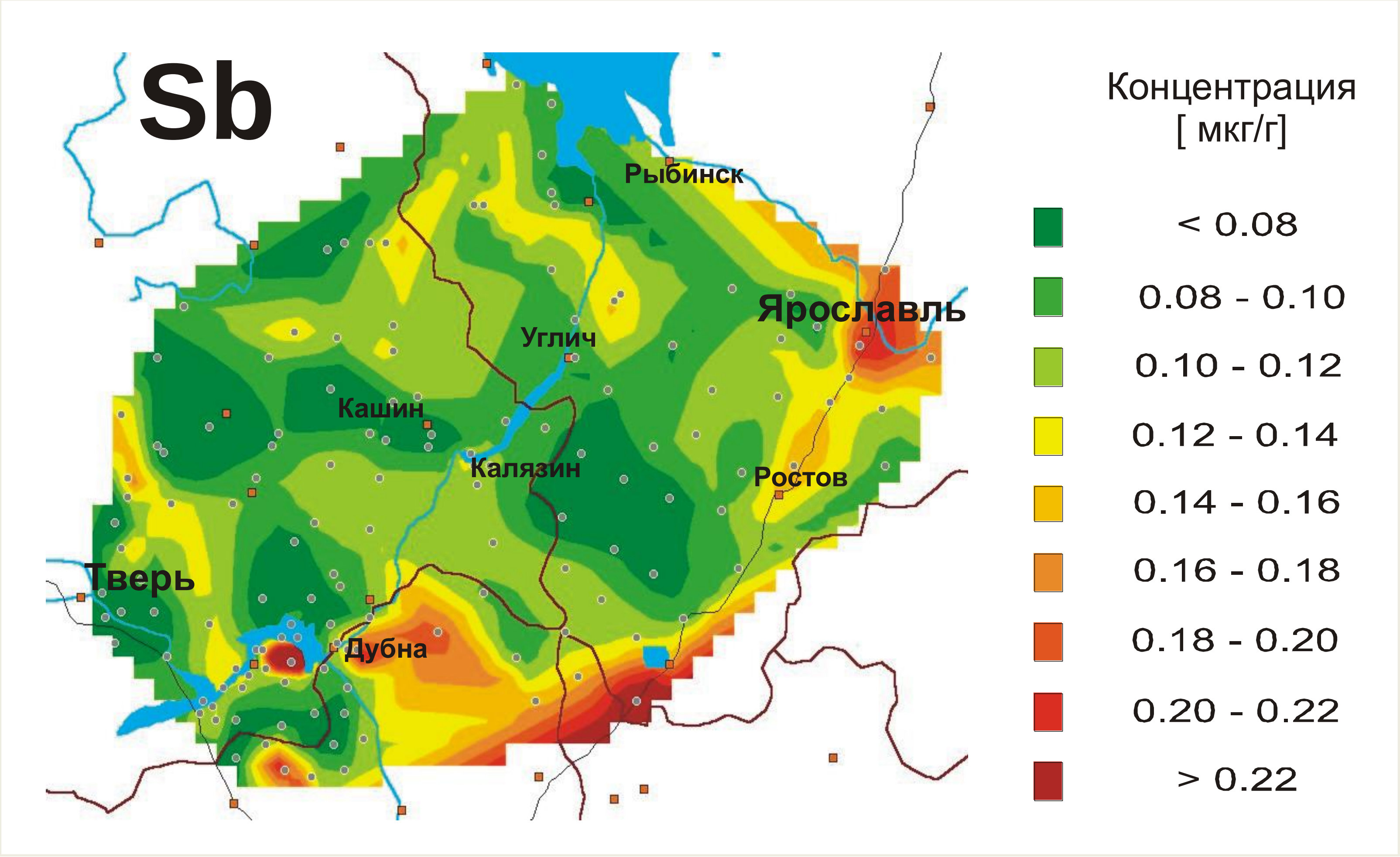
M.V. Frontasyeva, V.M. Nazarov and E. Steinnes. **Mosses as monitors of heavy metal deposition: Comparison of different multi-element analytical techniques.** In R.J. Allan and J.O. Nriagu, eds., *Heavy Metals in the Environment*, Vol.2, pp. 17-20. CEP Consultants, Edinburgh **1993**.


**The Main Areas of Research**

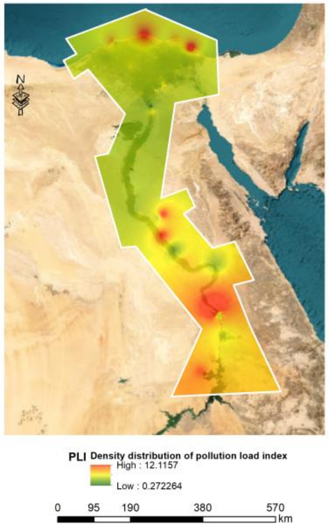
- Quality control of the air (study of aerosol filters, biomonitoring with mosses, lichens, etc.)
- Assessment of terrestrial and aquatic ecosystems (soil, sediments, biota)
- Geology and Geoecology
- Foodstuffs
- Materials Science (new and ultra–pure materials, new technologies)
- Biotechnology (development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

# *Example of the maps of the element distribution on the investigated territory (Tver' and Yaroslavl' Regions)*

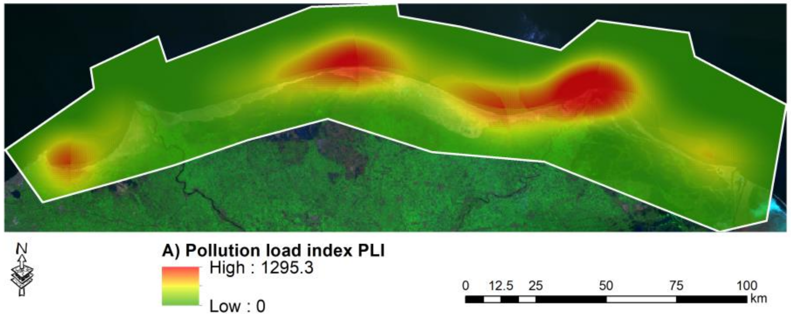


# Pollution load index (PLI) in Egypt

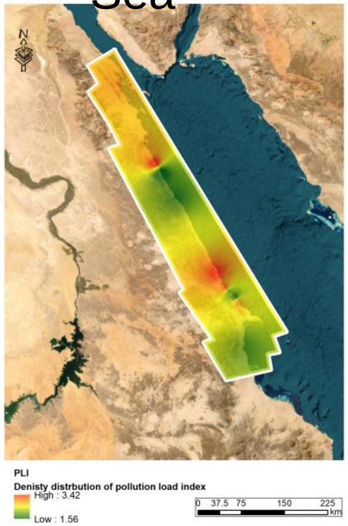
Nile River and Delta




Mediterranean Sea




Red Sea

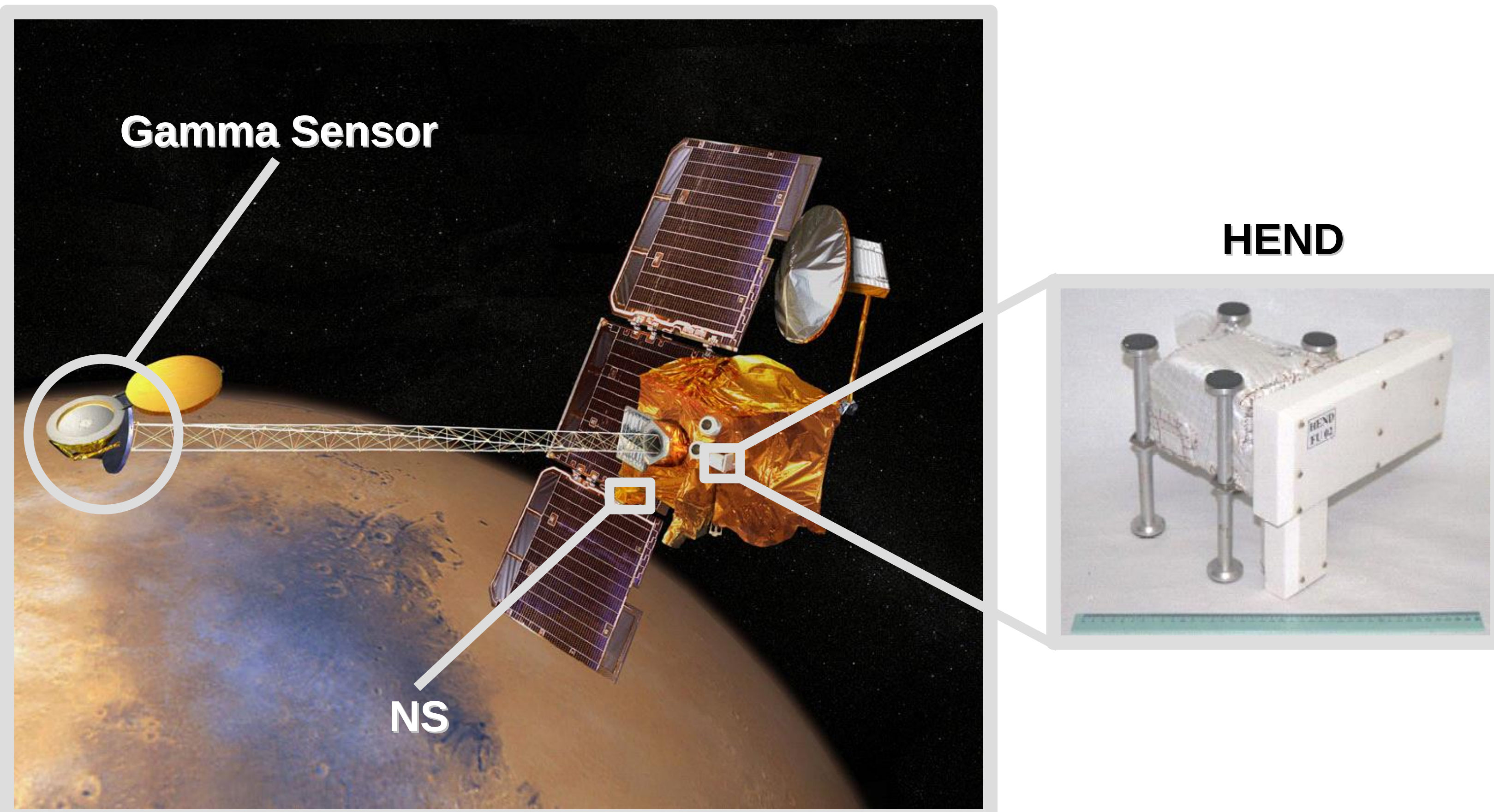



PLI was estimated to the studied areas and the obtained results are mapped as clearly seen. The results revealed that there are significant amounts of pollution in the upper Egypt (geogenic and anthropogenic sources) and estuary of the Nile to the Mediterranean sea and uncontrolled waste disposal in the lakes along the coastal areas. While for the Red Sea, the peak values were noticed where phosphate mining and transporting.

*W.Badawi et al.*

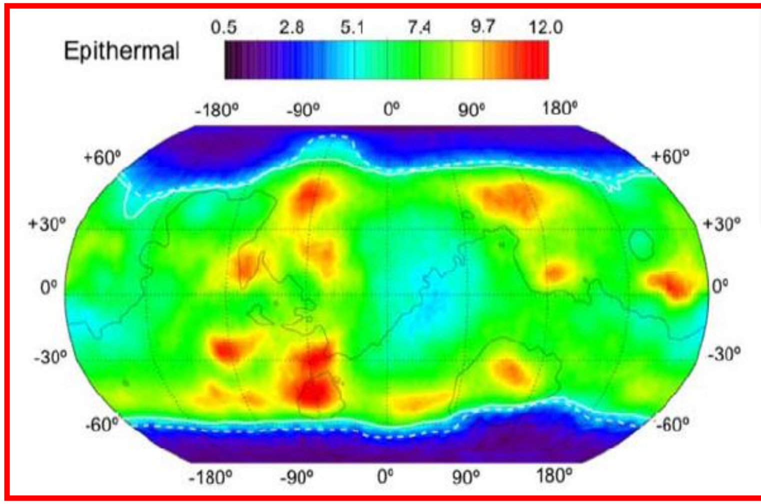
# Neutrons in Space

**2001 Mars Odyssey**

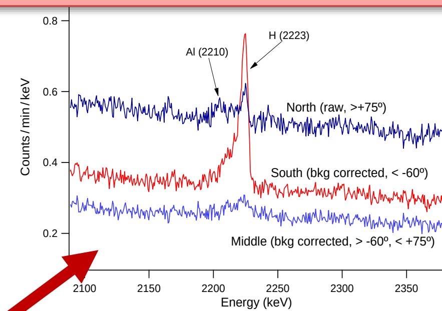


HEND operating on Martian orbit since 2002

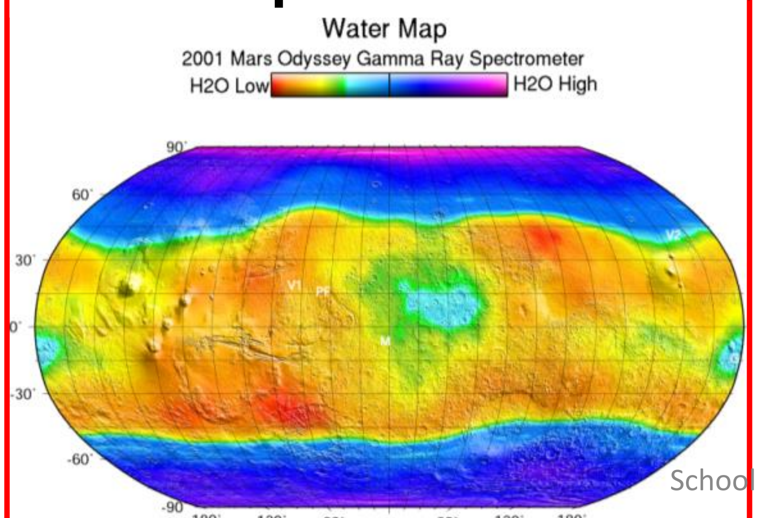
## Neutron Spectrometer



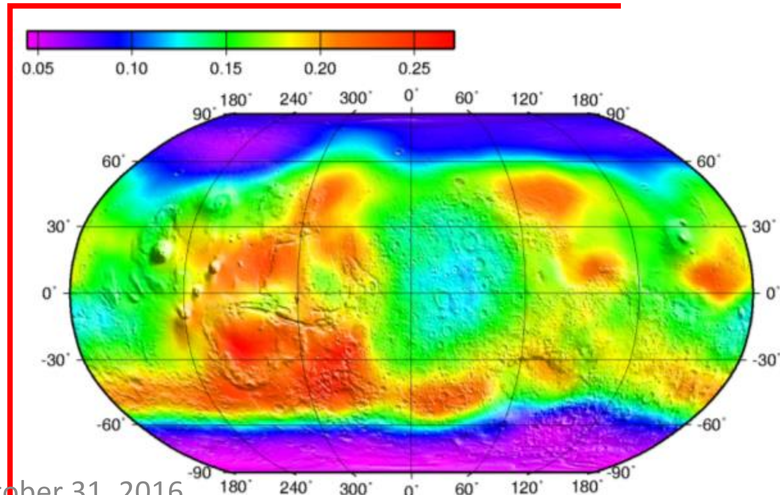

**Distribution of Hydrogen in the Near Surface of Mars: Evidence for Subsurface Ice Deposits. W. V. Boynton, W. C. Feldman, S. W. Squyres, T. H. Prettyman, J. Brückner, L. G. Evans, R. C. Reedy, R. Starr, J. R. Arnold, D. M. Drake, P. A. J. Englert, A. E. Metzger, Igor Mitrofanov, J. I. Trombka, C. d'Uston, H. Wänke, O. Gasnault, D. K. Hamara, D. M. Janes, R. L. Marcialis, S. Maurice, I. Mikheeva, G. J. Taylor, R. Tokar, and C. Shinohara. Science 5 July 2002: 81-85.Published online 30 May 2002 [DOI:10.1126/science.1073722]**



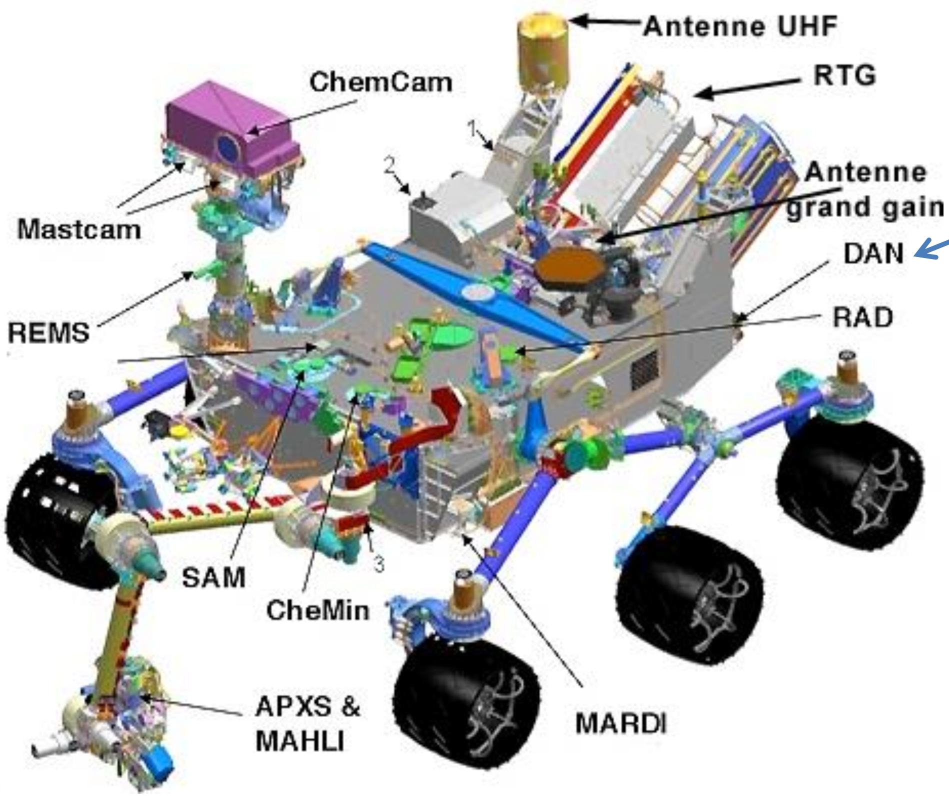

## Gamma Spectrometer

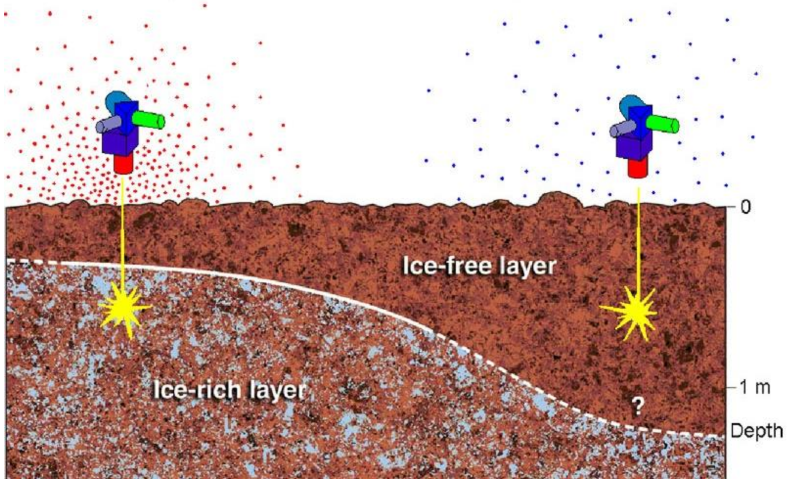



## HEND



# Dynamic albedo of neutrons on Curiosity



# Thank you for your attention!

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