Neutron Physics
at
FLNP JINR

O. A. Culicov

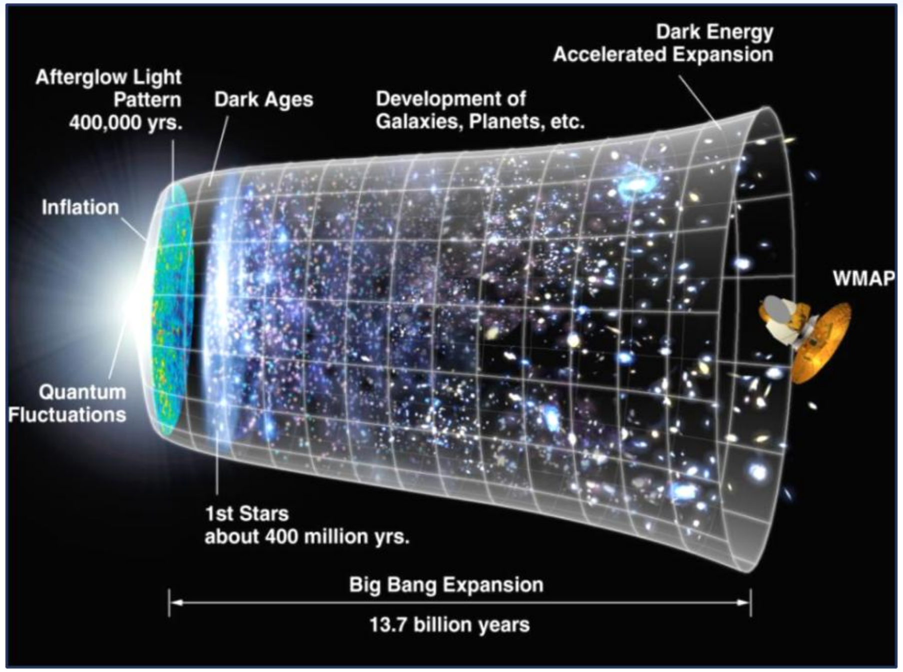
FLNP in the JINR landscape

- FLNP personnel is about 9 % of JINR staff
- Consists of more than 500 employees among them 1/3 scientists
- ~ 30 % of FLNP staff is younger 35
- FLNP staff's average age = 47 (JINR staff's average age = 52.1)
- A total of 112 non Russian employees ~ 20% of JINR non Russian employees
- ~ 27 % of FLNP staff is women

http://flnp.jinr.ru

FLNP personnel (besides the RF) as of 15.04.2018

Country	People	Younger than 35
Azerbaijan	12	11
Armenia	2	2
Belarus	1	1
Bulgaria	9	4
Czech Rep.	6	4
Cuba	3	2
Georgia	4	3
Germany	1	
Kazakhstan	20	20
Moldova	1	1
Mongolia	7	6
Poland	11	3
Romania	8	2
Slovakia	3	2
Tadjikistan	1	1
Turkey	1	1
Ukraine	15	12
Uzbekistan	1	1
Vietnam	6	4
TOTAL	**112**	**81**



Neutrons came into action at t=1 s after Big Bang when temperature went down to 10^9 K and formed nuclei could survive and interact with each other. Neutron lifetime – one of the key parameters of the Primordial Nucleosynthesis!

Since 10^9 years neutrons are governing the stellar nucleosynthesis!

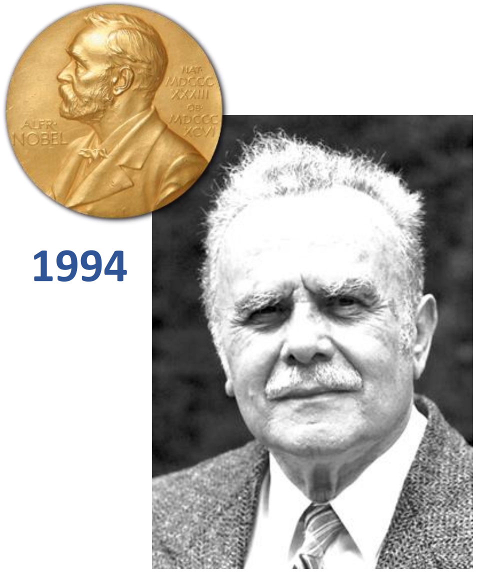
Neutron lifetime and beta-decay parameters – low energy approach to the Standard Model

Neutrons are driving force in nuclear power plants

SO NEUTRONS ARE EVERYWHERE

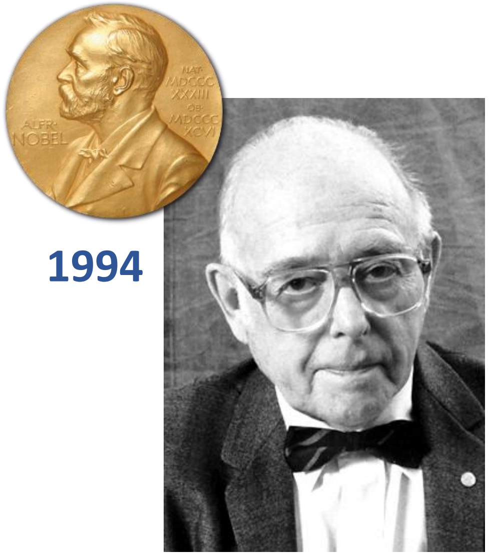
1935

James Chadwick
1891-1974
“ the discovery of the neutron”



1994

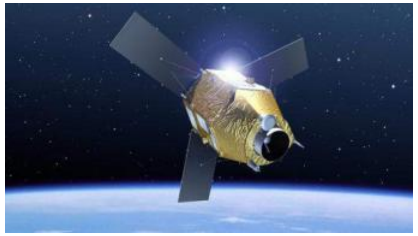
Bertram G. Brockhouse
1918-2003
"for the development of neutron spectroscopy"

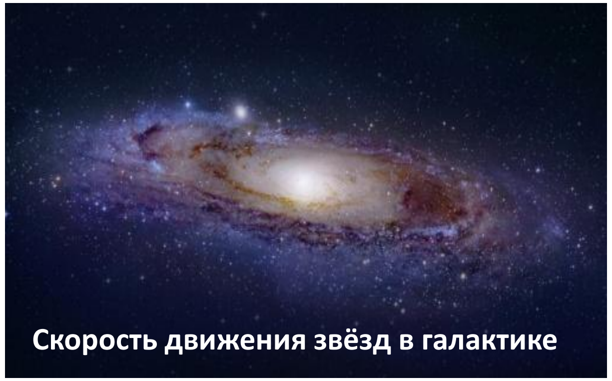


1994

Clifford N. Schull
1915-2001
"for the development of the neutron diffraction technique"

The Nobel Prize in Physics 1994 was awarded "for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter“.




Скорость движения звёзд в галактике


Скорости раекции ядерного синтеза


UCN
Thermal
CN
Resonance
Fast
υ
10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷
Скорость нейтронов, м/с
λ
10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹² 10⁻¹³ 10⁻¹⁴
Длина волны нейтрона, м
E
10⁻⁷ 10⁻⁵ 10⁻³ 10⁻¹ 10¹ 10³ 10⁵ 10⁷
Энергия нейтрона , эВ

Historical Overview

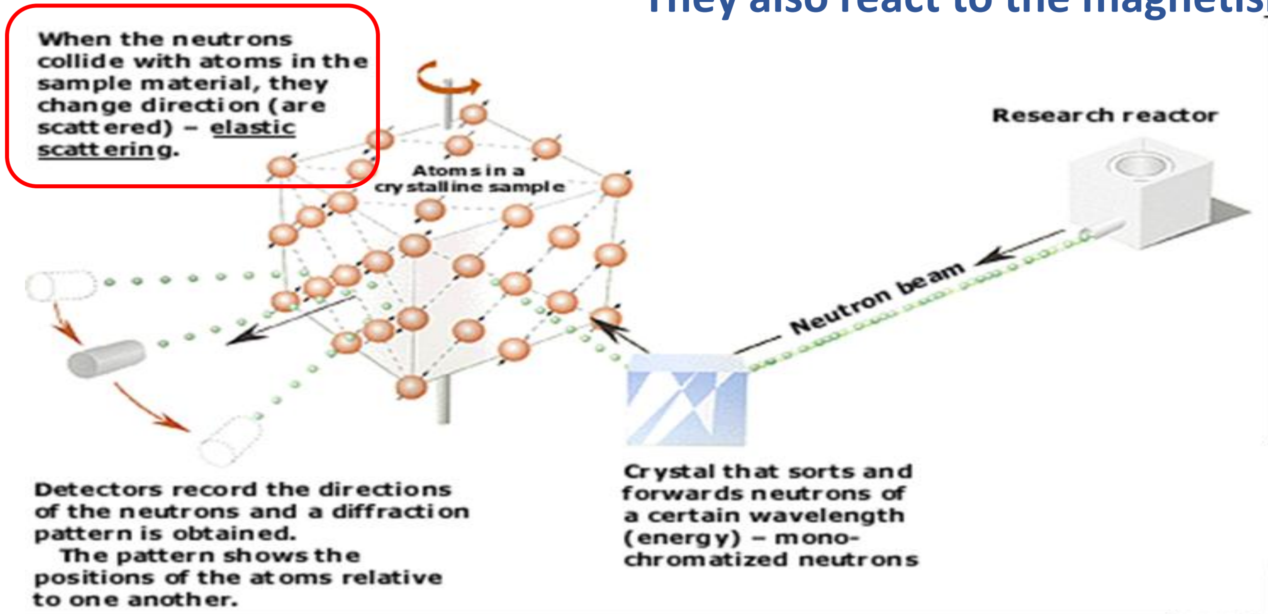
- 1895 – Wilhelm Röntgen – discovery of X-rays
- **1932 – James Chadwick - discovery of neutron**
- 1933 – Leó Szilárd – the idea of nuclear chain reaction
- 1937 – Glenn T. Seaborg – concept of nuclear spallation
- 1942 – Enrico Fermi – the first artificial nuclear reactor Chicago Pile-1
- 1947 – Elder, Gurewitsch, Langmuir and Pollock – observation of synchrotron radiation
- 1947-1993 & 1957 – National Research eXperimental & National Research Universal reactors
- 1950-1954 – Ernest O. Lawrence – the first spallation source Materials Testing Accelerator
- **1955 – Dimitry I. Blokhintsev – the idea of pulsed reactor**
- 1960-1968-2001 – Ilya M. Frank & Fyodor L. Shapiro – the pulsed reactor IBR, IBR-30
- 1961 – Synchrotron Ultraviolet Radiation Facility at NIST – the first generation synchrotron
- 1970 – Synchrotron Radiation Source at Daresbury, UK – the second generation: dedicated source
- 1971 – Institute Laue Langevin – the most intense continuous neutron flux reactor
- **1984-2006/2010-2037 – IBR-2, IBR-2M**
- 1994 – European Synchrotron Radiation Facility – the third generation: optimized for brightness
- 2006-present – Spallation Neutron Source operational
- 2017-future – X-ray Free Electron Laser – the fourth generation synchrotron
- 2019-future – European Spallation Source constructing

What the neutrons do?

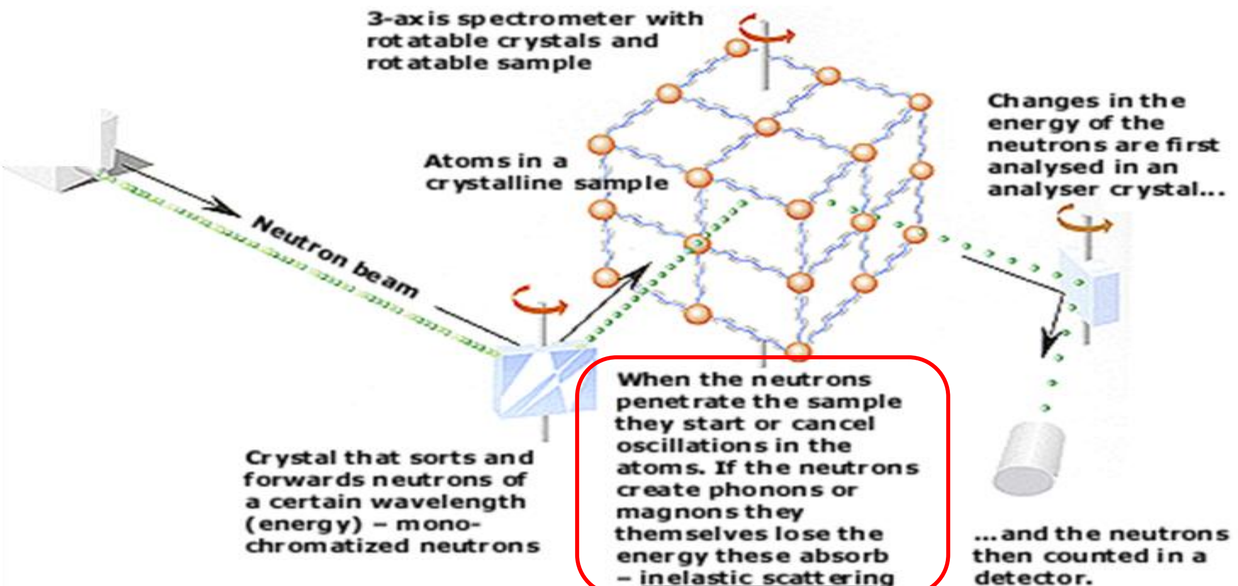
Neutrons reveal structure and dynamics

Neutron bounce against atomic nuclei

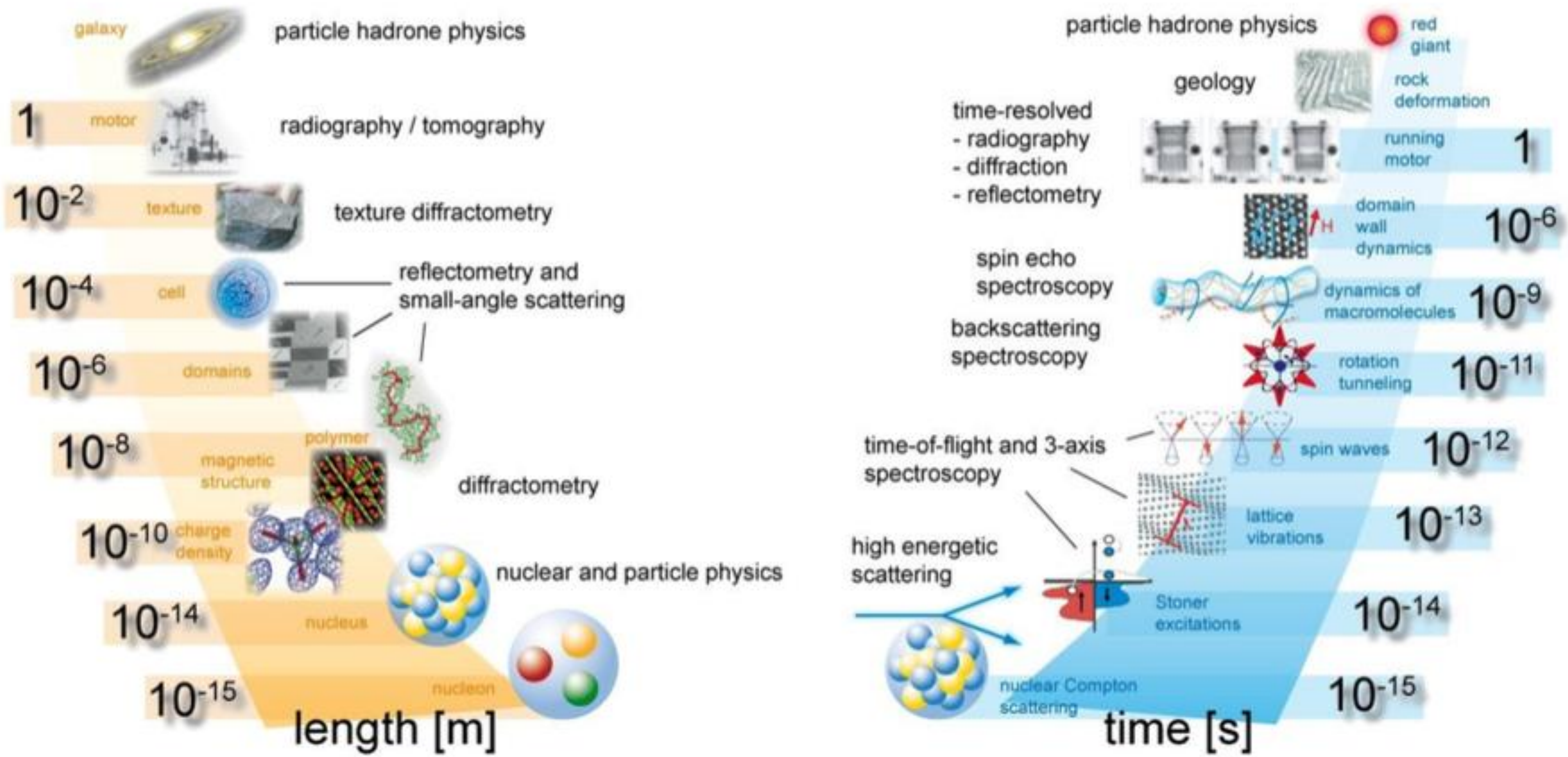
They also react to the magnetism of the atoms



- Neutron shows where atoms are



- Neutron shows what atoms do


galaxy
particle hadrone physics
1
motor
radiography / tomography
10-2
texture
texture diffractometry
10-4
cell
reflectometry and
small-angle scattering
10-6
domains
10-8
polymer
magnetic
structure
diffractometry
10-10
charge
density
nuclear and particle physics
10-14
nucleus
10-15
nucleon
length [m]
particle hadrone physics
red
giant
geology
rock
deformation
time-resolved
- radiography
- diffraction
- reflectometry
running
motor
1
domain
wall
dynamics
10-6
spin echo
spectroscopy
dynamics of
macromolecules
10-9
backscattering
spectroscopy
rotation
tunneling
10-11
time-of-flight and 3-axis
spectroscopy
spin waves
10-12
lattice
vibrations
10-13
high energetic
scattering
Stoner
excitations
10-14
nuclear Compton
scattering
10-15
time [s]


2000
1990
1980
1970
1960
Biotechnology
Drug design
Pharmacology
Materials processing
Environment
Clean technology
Catalysis
Energy storage
New materials
Energy transmission
Transport
Data storage
Quantum devices
Proteins
Surfactants
Polymers
Catalysts
Water in biology
Minerals
Stress
Buckyballs
Hydrogen bonding
Phase transitions
Superconductivity
Vortex lattice
Antiferromagnetism
Phonons
Quantum fluids
Spin dynamics
Achievements of neutron scattering
– the evolution and diversification of neutron scattering over the past 40 years

Neutron sources (classification by significance)

- Large (Significant) neutron sources
  - Nuclear reactors
    - Steady state reactors (U-235, U-233, Pu-239);
    - Pulsed reactors;
  - Fusion Systems (D+T)
  - Spallation Sources (p + heavy target)
- Medium neutron sources
  - Bremsstrahlung from Electron Accelerators ($e^- \rightarrow Pb \rightarrow \gamma \rightarrow Pb \rightarrow (\gamma,n)$)
  - Dense plasme focus (short-lived plasma of D/T)
  - Light ion accelerators (H, D or T nuclei on D, T, Li, Be, other low Z-elements)
- Small neutron sources
  - Neutron Generators ($^2D + ^3T \rightarrow ^4He + n + 17.6$ MeV)
  - Radioisotope sources
    - (α,n) reactions $^4He + ^9Be \rightarrow ^{12}C + n + 5.7$ MeV, Ra, Pu or Am as α-emitter
    - (γ,n) reactions $^{124}Sb \rightarrow ^{124}Te + \beta^- + \gamma$; $\gamma + ^9Be \rightarrow ^8Be + n - 1.66$ MeV
    - Spontaneous fission Cf-252

The birth of a pulsed fast reactors idea

1908-1979

The story starts in Obninsk (south of Moscow) in 1955 when Professor Blokhintsev (at that time Director of the research laboratory in Obninsk, from 1956 – first JINR Director) during one regular seminar expressed an idea to build a pulsed reactor source.

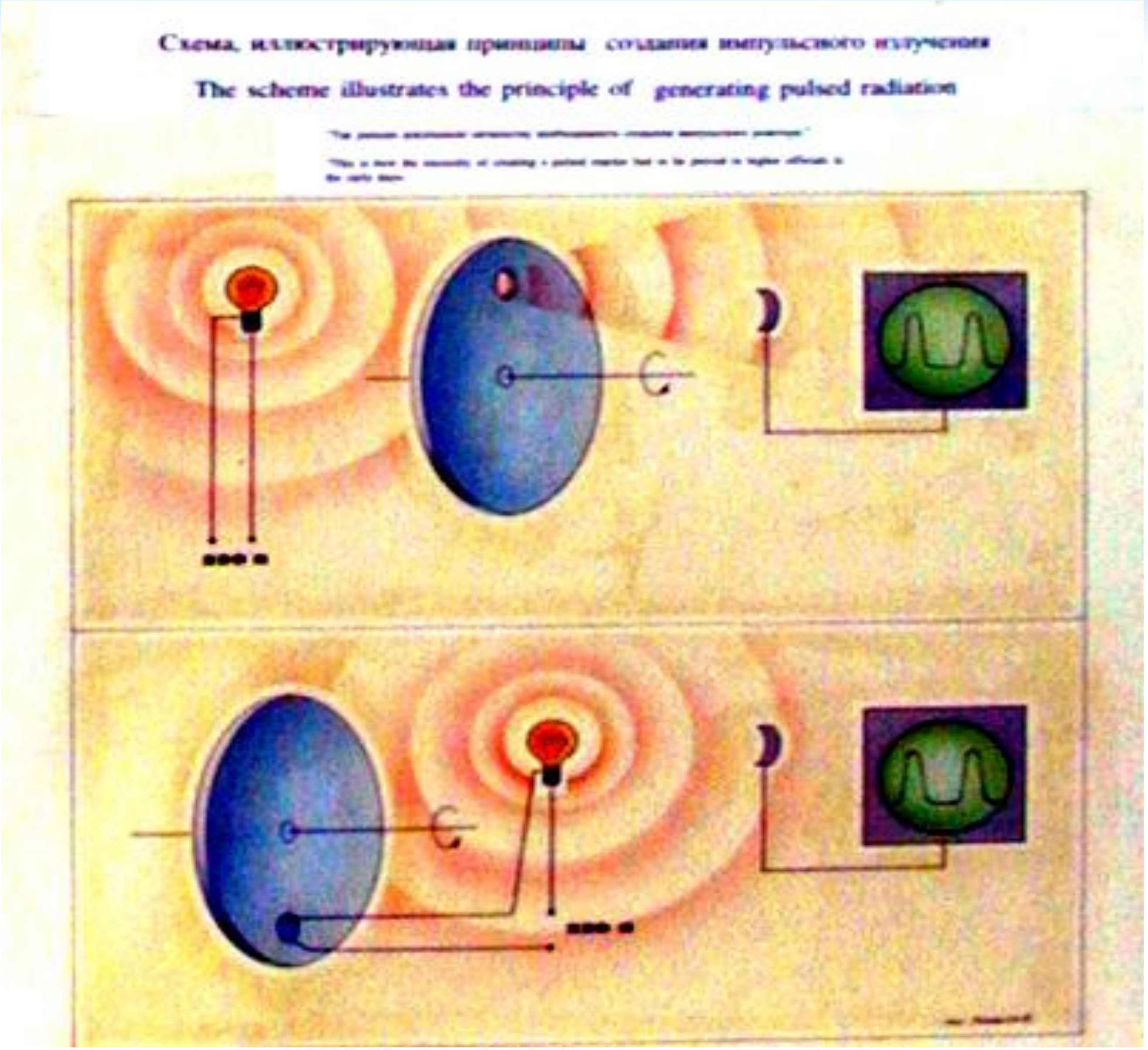


Illustration of the idea
after D.I.Blokhintsev
(“*for high level bureaucracy*”)

IBR idea

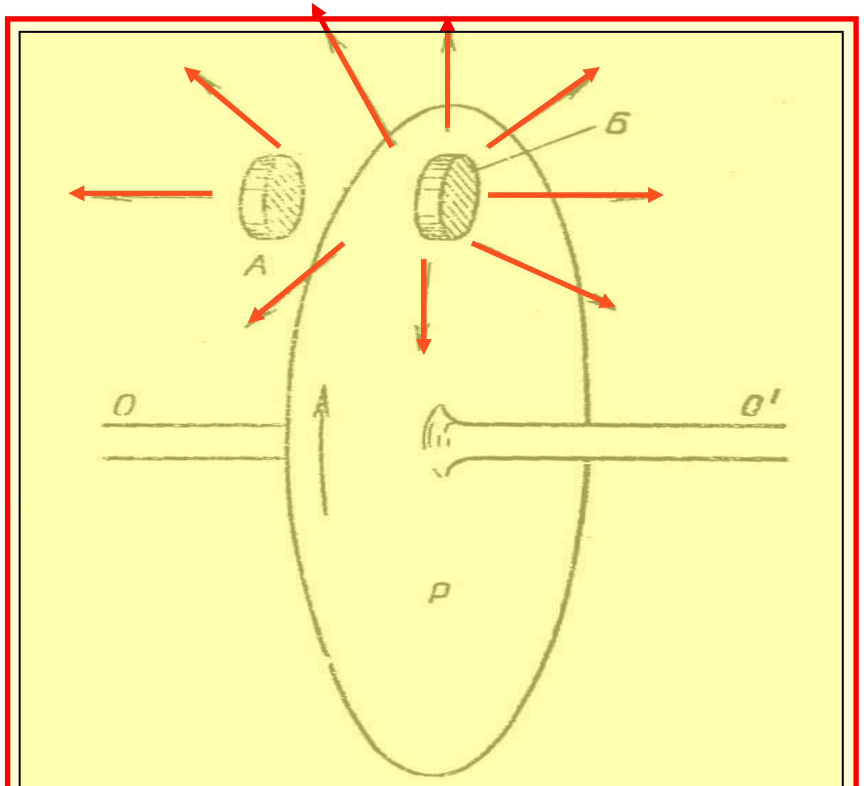


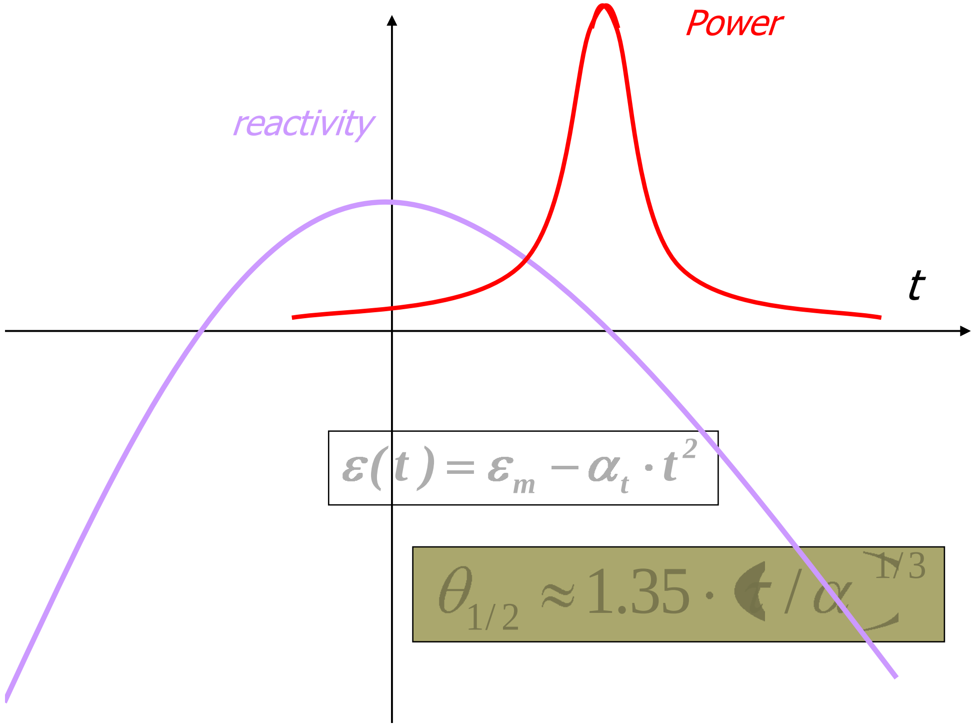
Рис. 7. Принцип действия периодического импульсного реактора ИБР:

Р — быстро вращающийся диск — ротор; Б — кусок урана, вмонтированный в диск; А — статор — неподвижный кусок урана; стрелки показывают поток нейтронов в момент прохождения Б около А

Idea (1955) – D.I.Blokhintsev

Theory (1956) – I.I.Bondarenko,
Yu.Ya.Stavisski

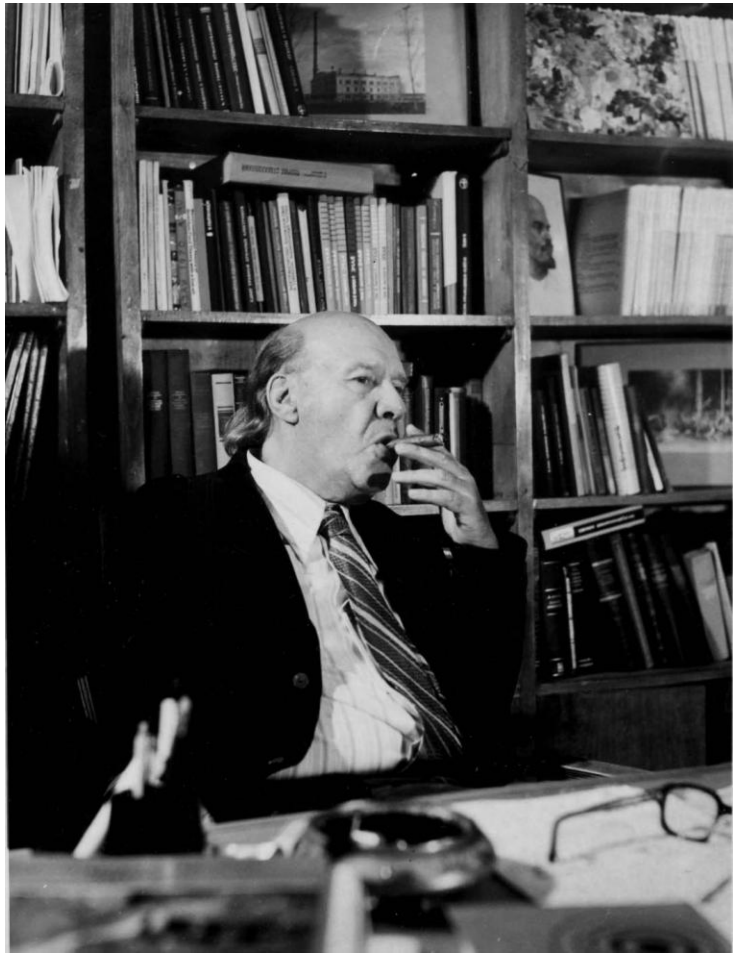
IBR theory was further developed by Shabalin, Govorkov, Asaoka, Larrimore, Blaeser, Schwalm, Kozik.



$$\varepsilon(t) = \varepsilon_m - \alpha_t \cdot t^2$$

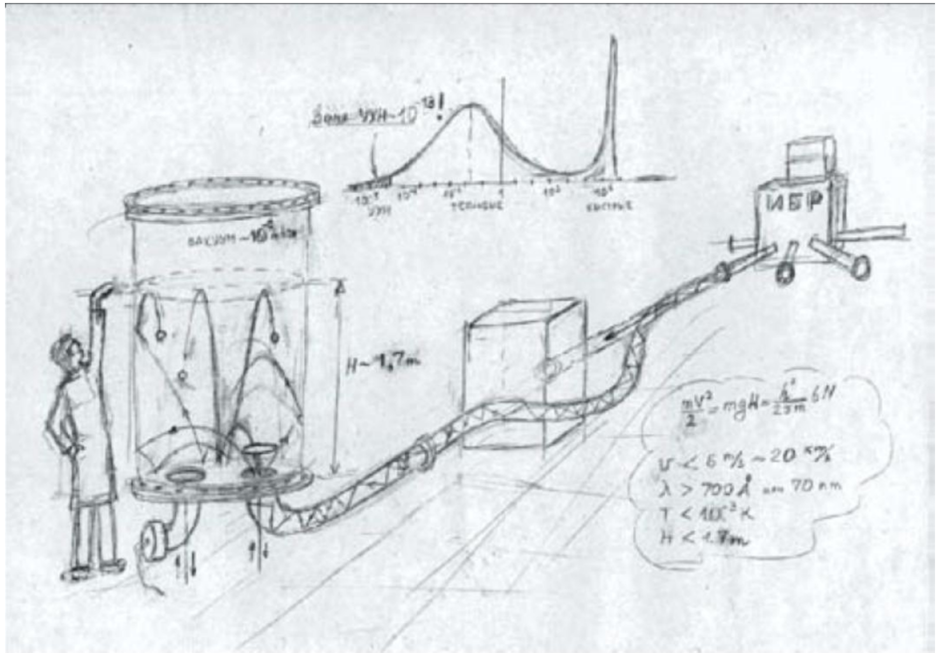
$$\theta_{1/2} \approx 1.35 \cdot (\varepsilon/\alpha)^{1/3}$$

Blokhintsev characterised the principle of IBR operation as – «teasing tiger in a cage 50 times per second».



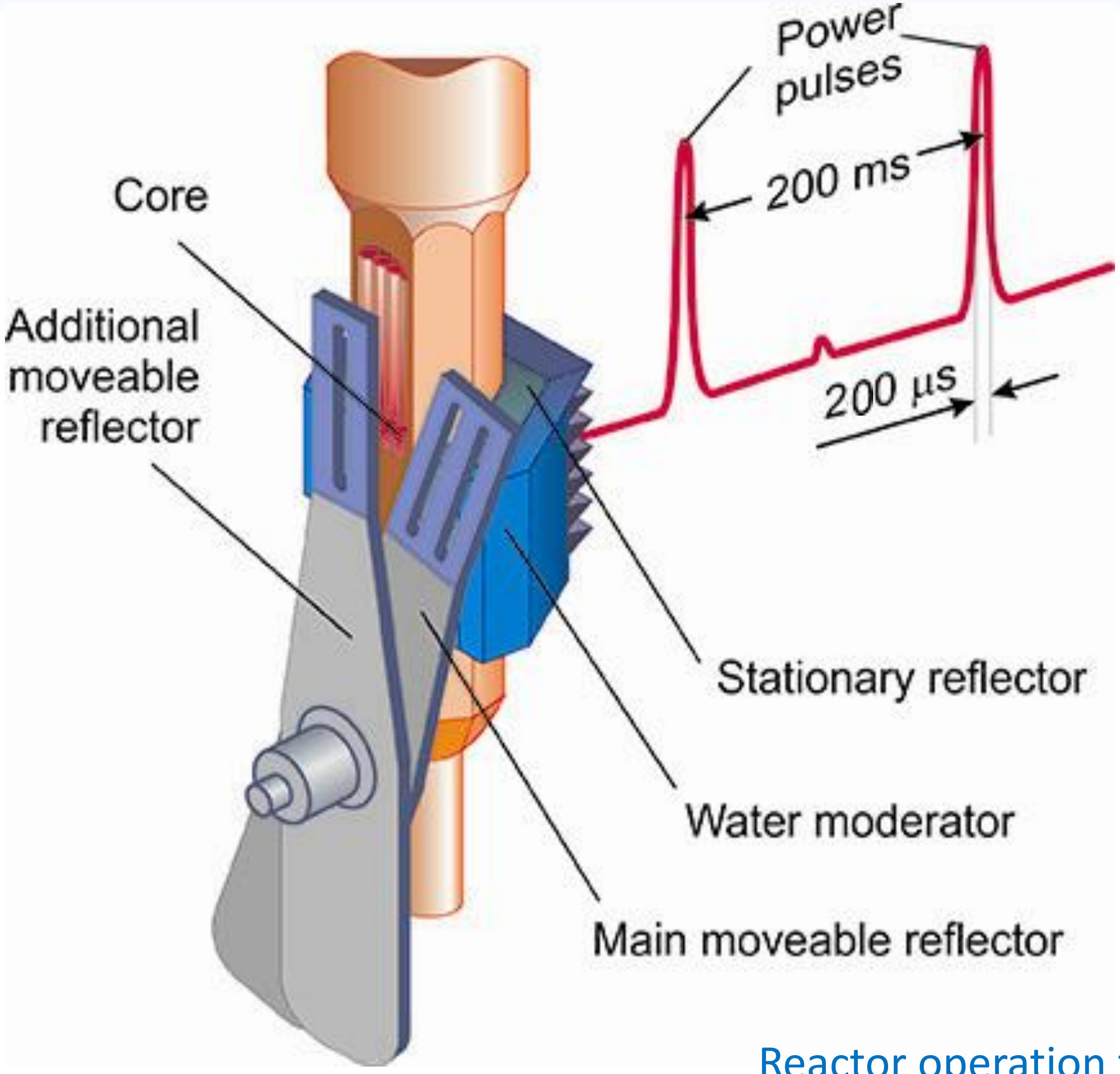
1960-1968

IBR: the first pulsed fast reactor in the world…..



…was the place where the ultracold neutrons where discovered.

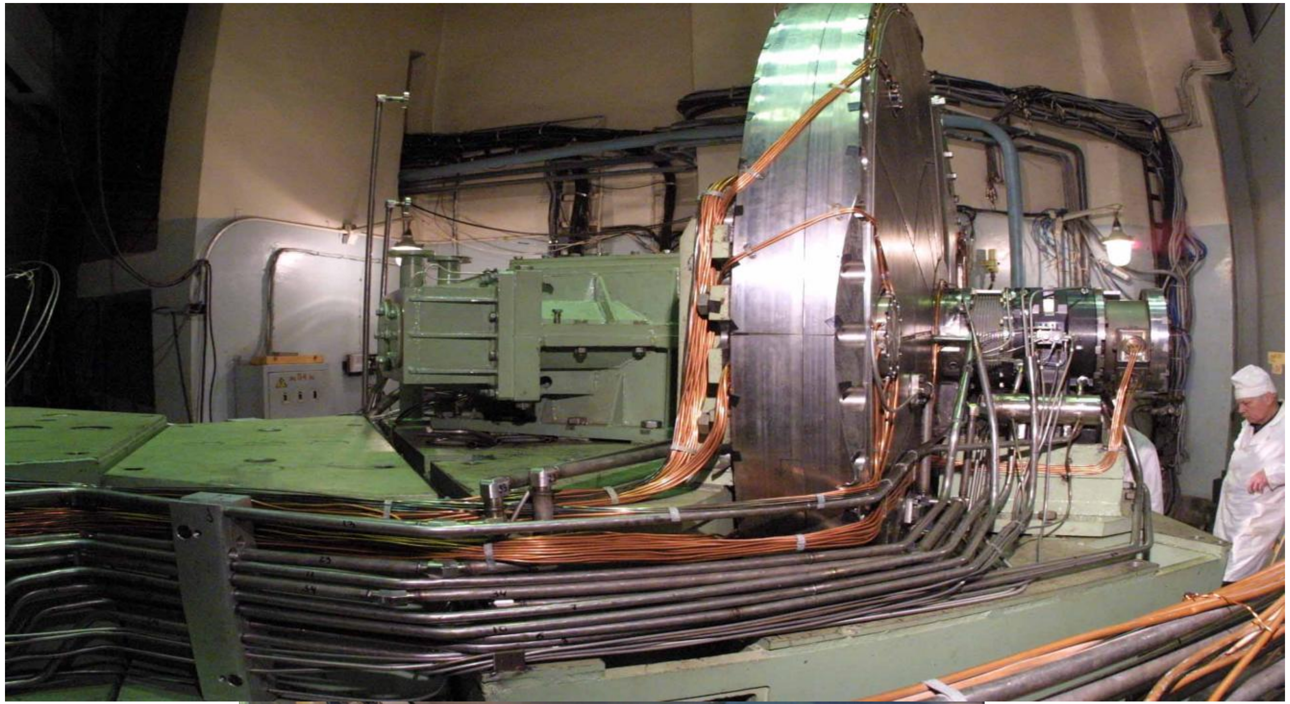
IBR-2 Reactor

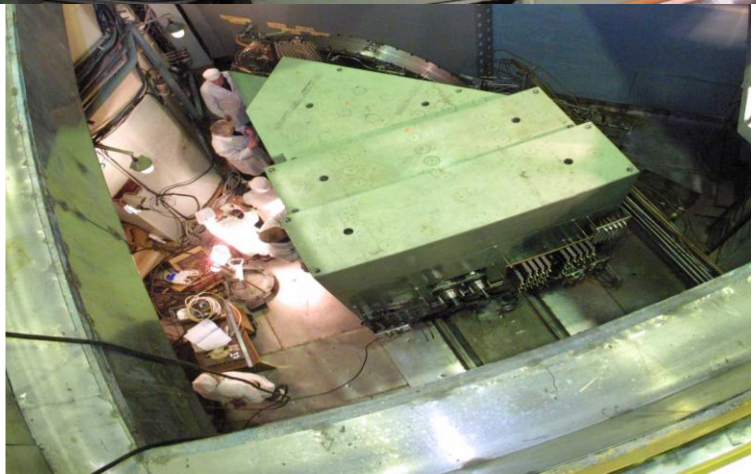


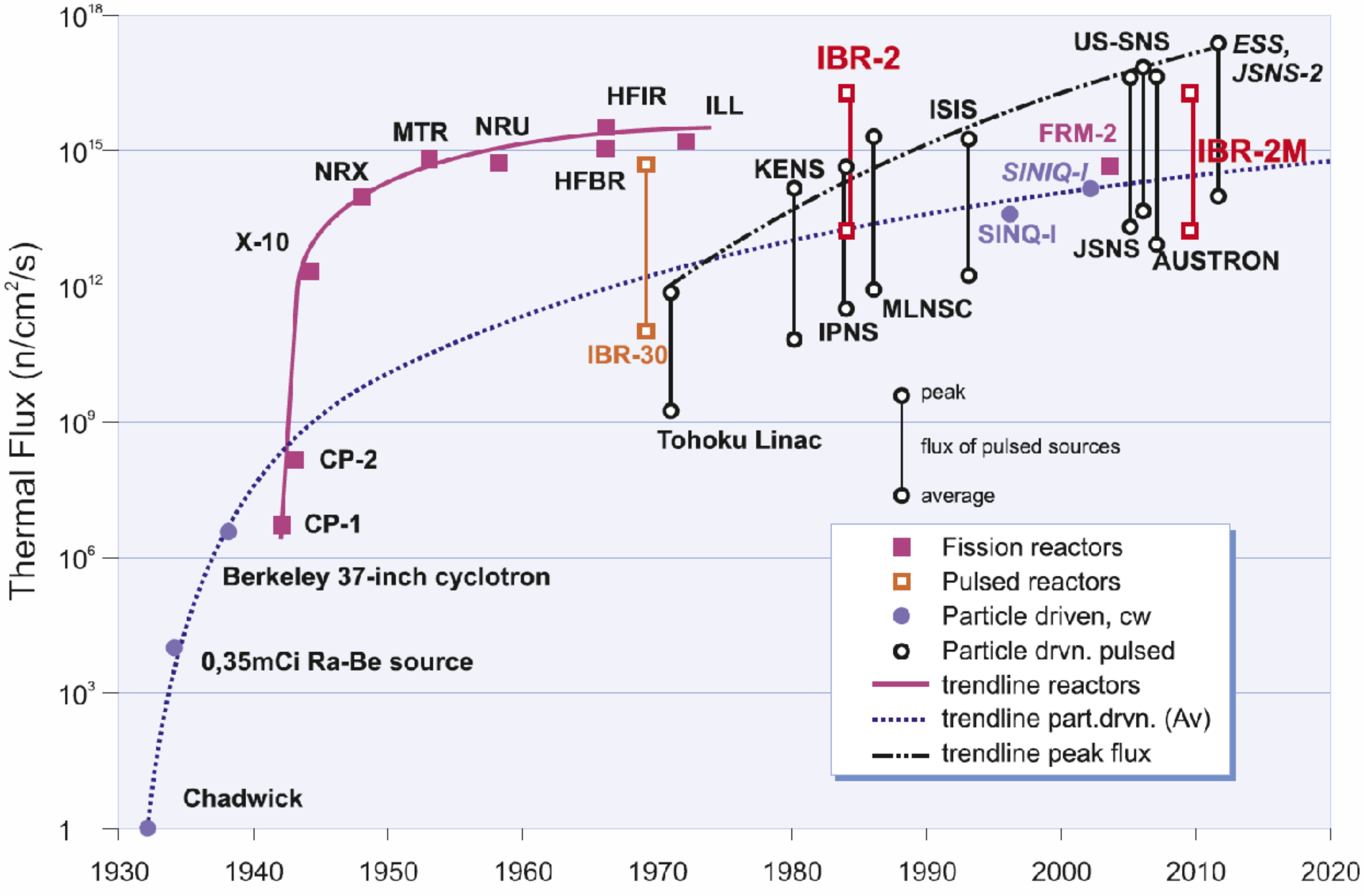
Average power, MW	2
Fuel	PuO_2
Number of fuel assemblies	69
Maximum burnup, %	9
Pulse repetition rate, Hz	5; 10
Pulse half-width, µs:	
fast neutrons	200
thermal neutrons	340
Rotation rate, rev/min:	
main reflector	600
auxiliary reflector	300
MMR and AMR material	nickel + steel
MR service life, hours	55000
Background, %	7.5
Thermal neutron flux density from the surface of the moderator:	
- time average	~ 10^{13} n/cm²·s
- burst maximum	~ 10^{16} n/cm²·s

Reactor operation for physics experiments, hr/year ~2500

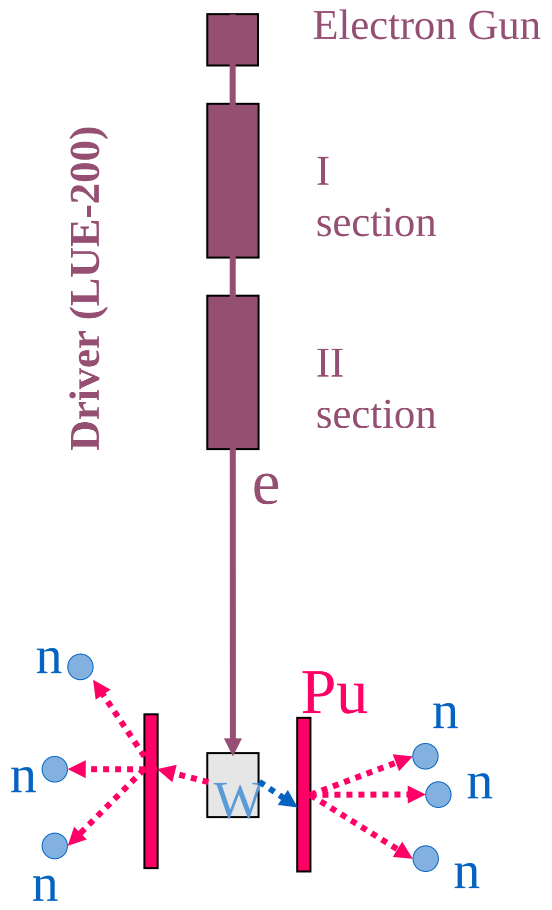
The movable reflector



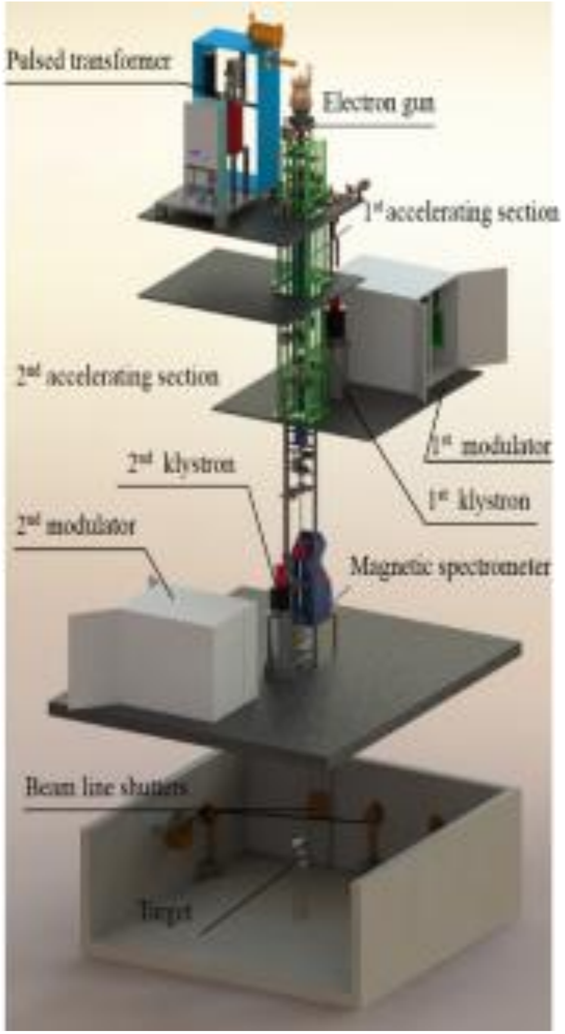



Thermal Flux (n/cm²/s)
1
10³
10⁶
10⁹
10¹²
10¹⁵
10¹⁸
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Chadwick
0,35mCi Ra-Be source
Berkeley 37-inch cyclotron
CP-1
CP-2
X-10
NRX
MTR
NRU
HFIR
ILL
HFBR
IBR-30
Tohoku Linac
KENS
IBR-2
IPNS
MLNSC
ISIS
FRM-2
SINIQ-I
SINQ-I
US-SNS
JSNS
AUSTRON
IBR-2M
ESS,
JSNS-2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

Conception of IREN neutron source



Target – Converter



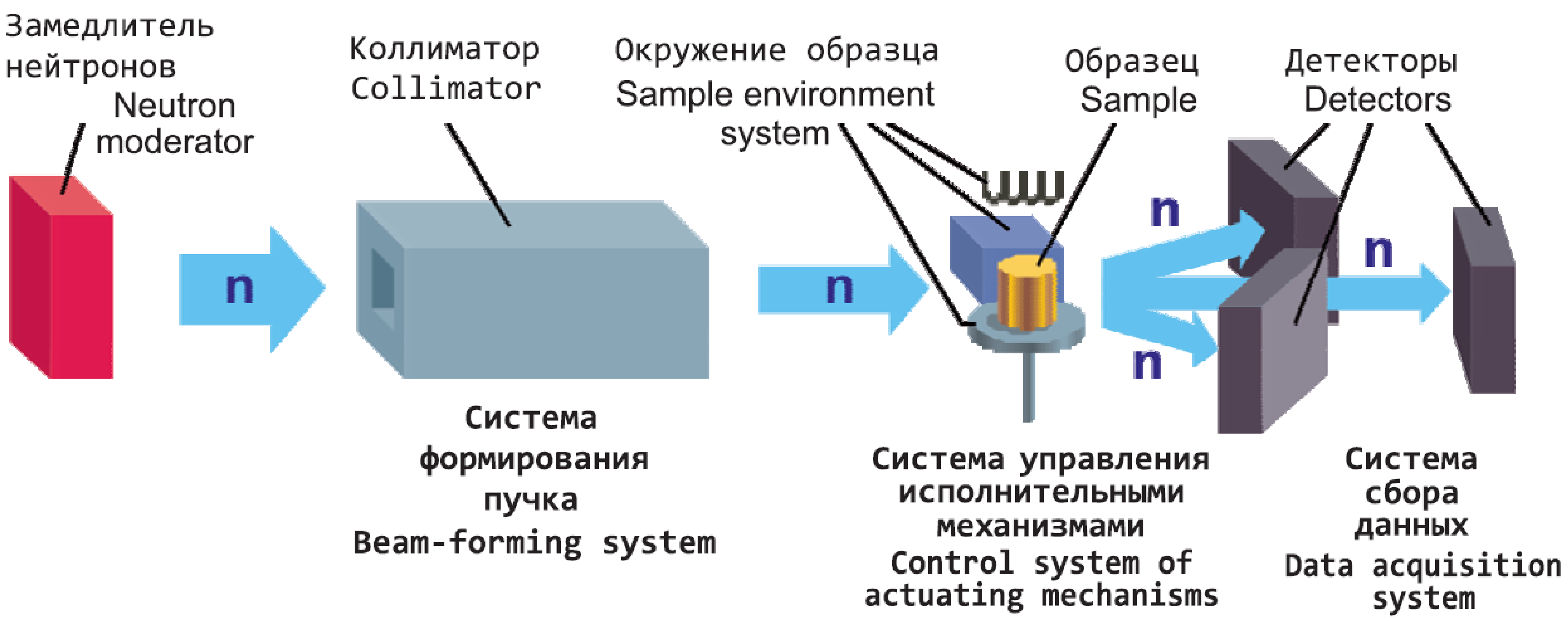
Technical parameters	
Peak current, A	3
Repetition rate, Hz	50
Electron pulse duration, ns	100
Electron energy, MeV	30
Beam power, kW	0.4
Multiplication	1
Neutron intensity, n/s	10^{11}

Electron accelerator based neutron sources – nuclear data mining facilities

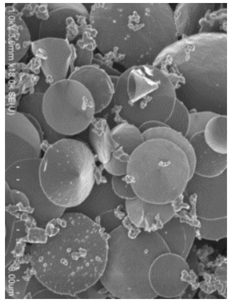
Facility	Location	particle	E, MeV	Target	Pulse width, ns	Beam power, kW	Pulse rate, Hz	Flight paths, m	Neutron yield, s^{-1}
RPI	RPI, Troy, USA	e-	60	Ta	5, 5000	0.45	500	15-250	$1.8 \cdot 10^{12}$
ORELA	ORNL, Oak Ridge, USA	e-	180	Ta	2-30	60	12-1000	9-200	$1.0 \cdot 10^{14}$
GELINA	EC-JRC-IRMM, Geel, Belgium	e-	100	U	1	10	40-800	5-400	$3.4 \cdot 10^{13}$
PNF	PAL, Pohang, Korea	e-	75	Ta	2000	0.09	12	11	$2.1 \cdot 10^{11}$
KURRI	Kumatori, Japan	e-	46	Ta	2, 4000	6	300	10, 13, 24	$8.0 \cdot 10^{11}$
IREN now	JINR, Dubna, Russia	e-	50	W	100	0.4	25	10-500	$3.0 \cdot 10^{11}$

IREN is already in the list of world electron accelerator based facilities

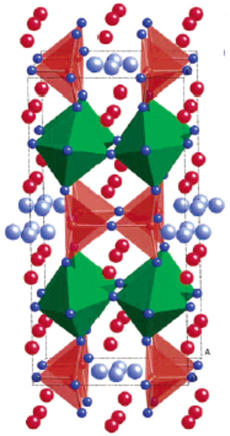
Neutron spectrometer for condensed matter investigations



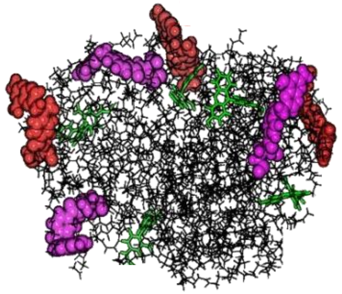
The priority directions of fundamental research :



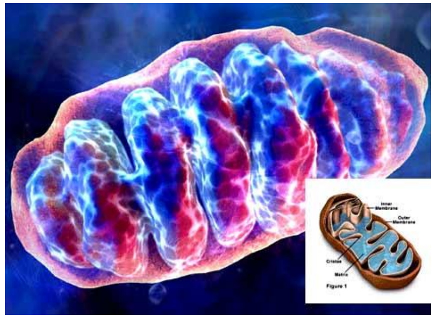
- Nanoscale physics



- Physics and Chemistry of Functional Materials

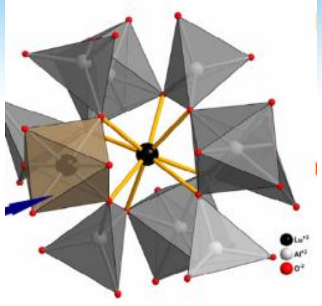


- Physics and Chemistry of
  Complex Liquids and Polymers

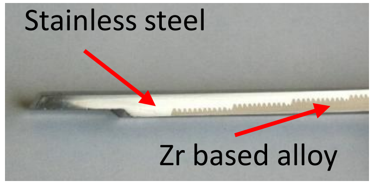


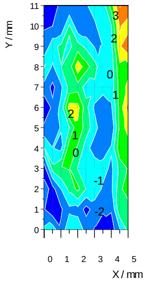
- Physics of Soft Condensed Matter

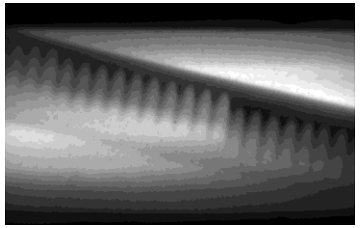
The priority directions of applied research:



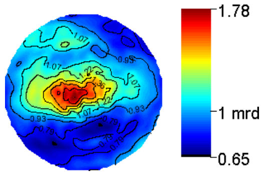
- Structural characterization of functional materials used in different (nano)technologies

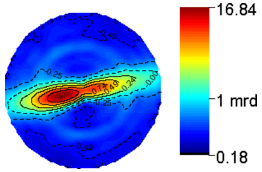






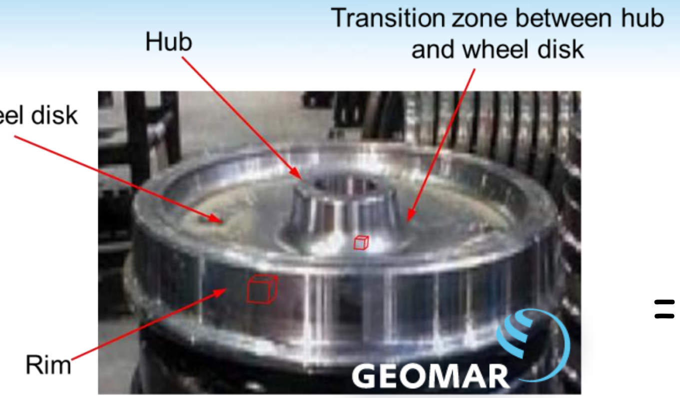
- Non-destructive control of residual stresses and internal organization of bulk materials and products





- Texture analysis of geomaterials and constructional materials

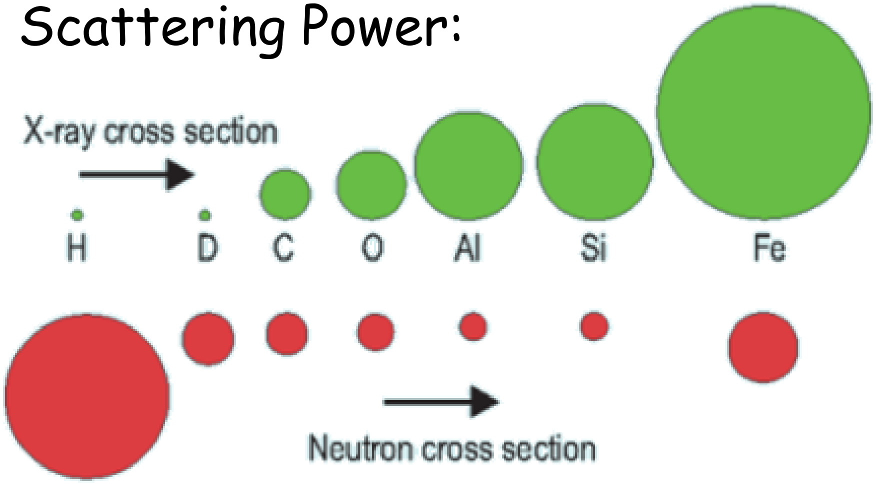
Advantages of Neutrons



- No Charge: ==> deep penetration into matter

- Magnetic Moment: ==> the world smallest magnetometer

- Scattering Power: ==> sensitivity to light elements
  ==> sensitivity to isotope exchange

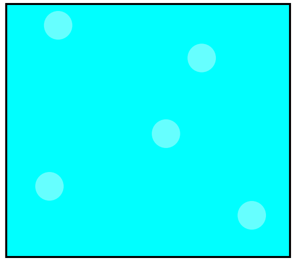


Contrast Variation in Neutron Scattering

Scattered intensity is proportional to

Contrast

"the square of the difference between scattering length density of studied material and medium"

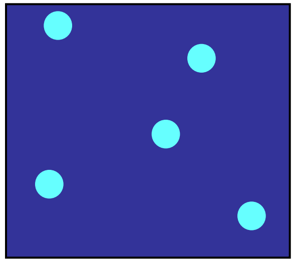


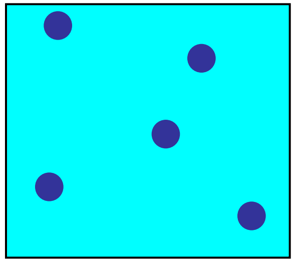
Neutron contrast variation can be done without changing the chemical properties of the system, because the neutron scattering lengths of isotopes can be very different.

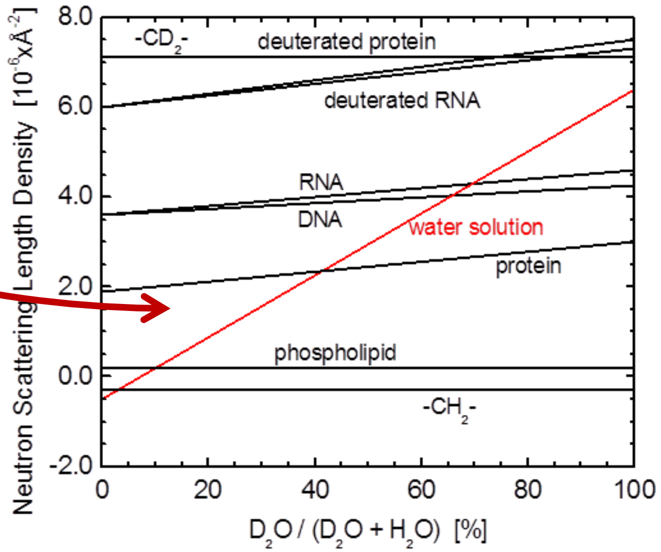
low contrast

increased contrast

great for biomaterials!



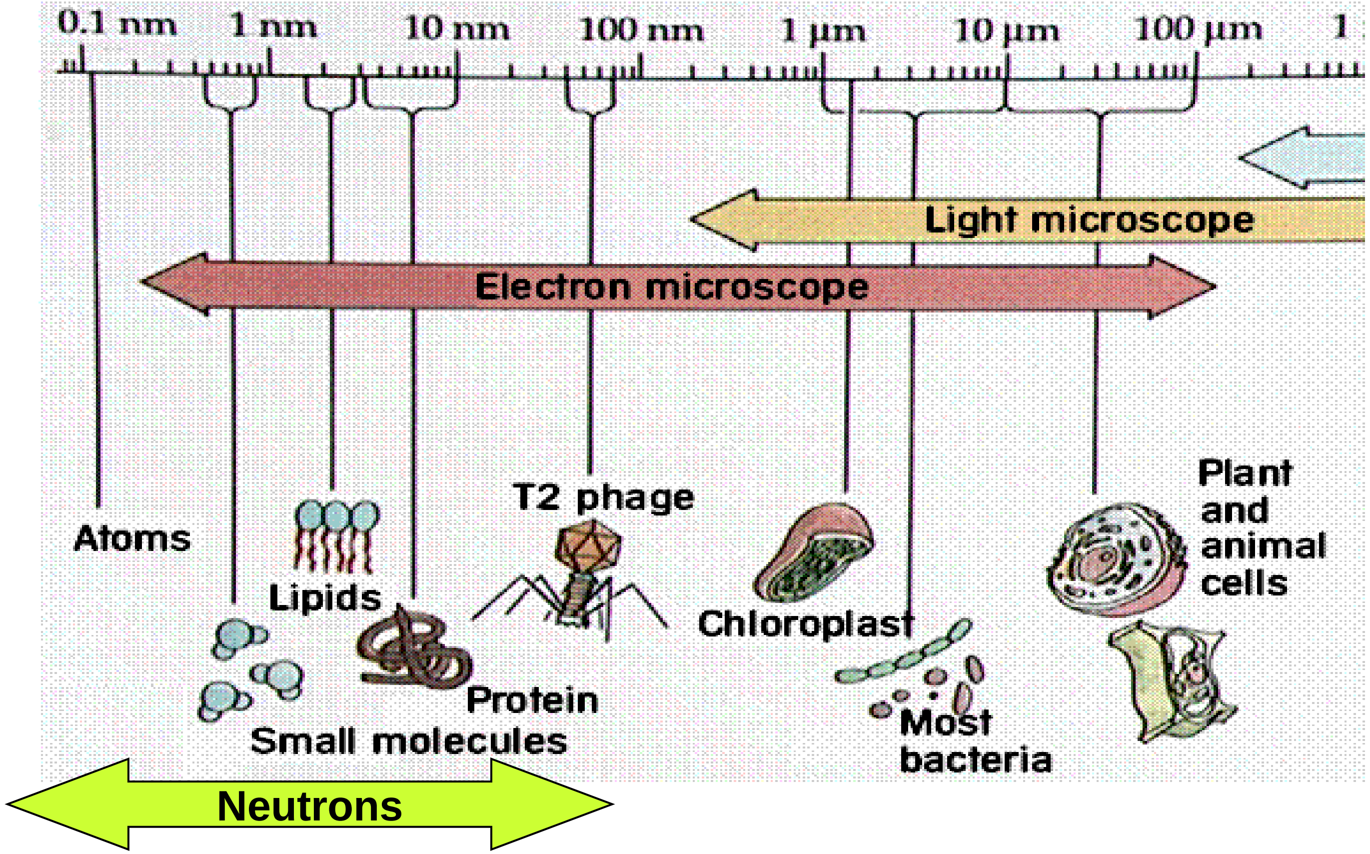




In biology D2O/H2O mixtures can match out the protein, lipid, nucleic acid, etc. after allowing for D – H exchange

Soft matter and biology:

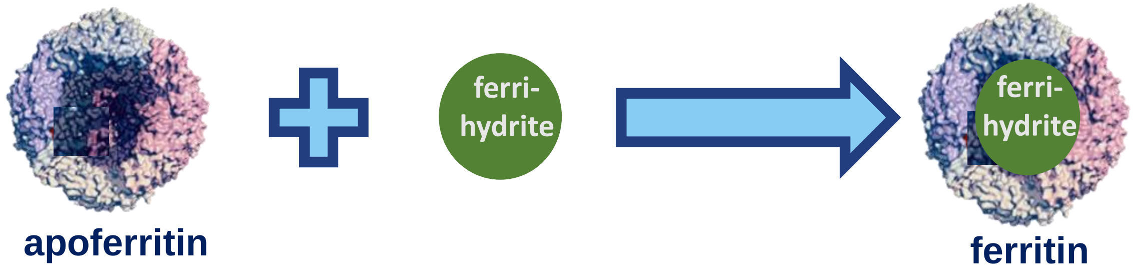
from simplicity to complexity



Atoms & molecules ➡ Self organization ➡
Folding & aggregation ➡ Structure ➡ Dynamics & function

- Structural biology, as well as biotechnology, benefits from the powerful ability of neutrons to contribute to the location of hydrogen atoms and water molecules in biological systems.
- Thus it contributes to the production of missing complementary data relevant for molecular modelling and to the strategy of rational drug design, in synergy with other biophysical approaches.

Investigation of Bio-Macromolecules

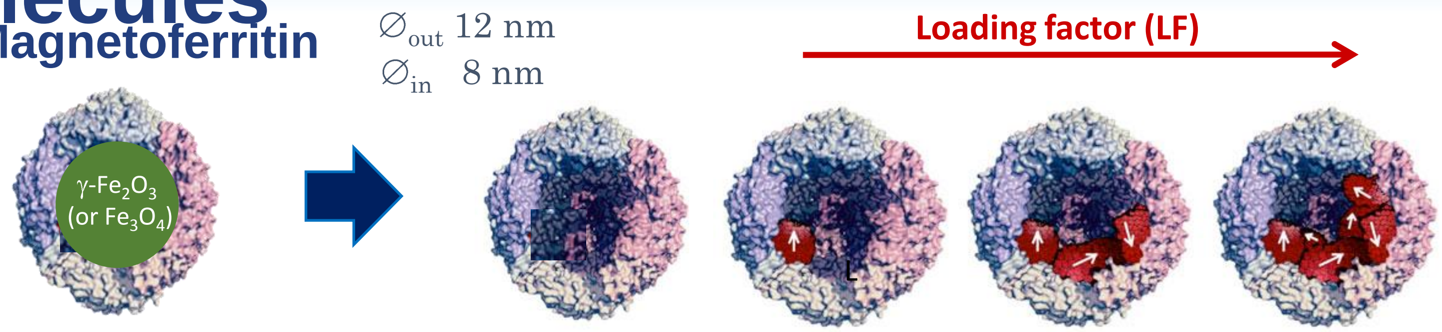


World Health Organization

- Iron is an essential element for living organisms but is highly toxic in excess.
- Iron deficiency anemia is the most common single cause of anemia worldwide.
- Living organisms store iron to provide an appropriate concentration and at the same time to protect themselves against the toxic effects of iron excess.
- The major intracellular storage form of iron is ferritin. Ferritin is the "buffer" against either iron deficiency or iron overload: if the blood has too little iron, ferritin can release more. If the cells have too much iron, ferritin can help to store the excess iron.
- The structure of ferritin consists of a spherical protein shell (apoferritin) surrounding an aqueous cavity.
- Fe^{2+} is oxidized and transported into the ferritin interior and deposited as an iron

Interactions of Nanoparticles with Bio-Macromolecules

Magnetoferritin

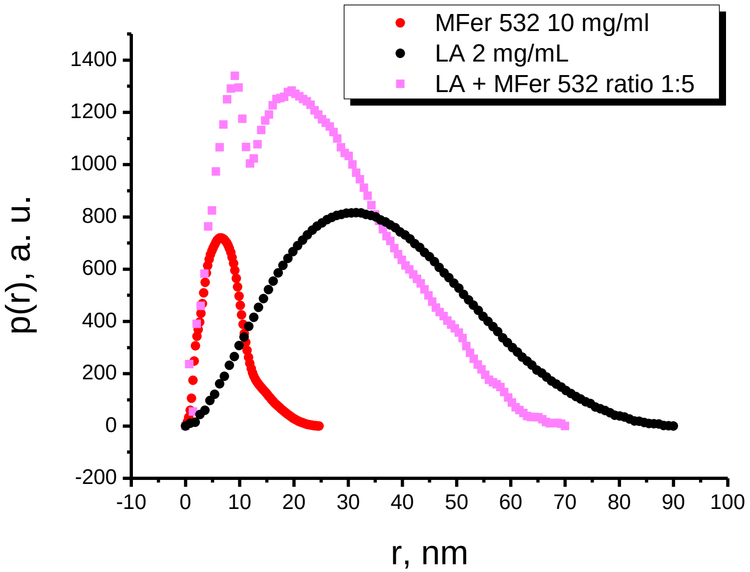


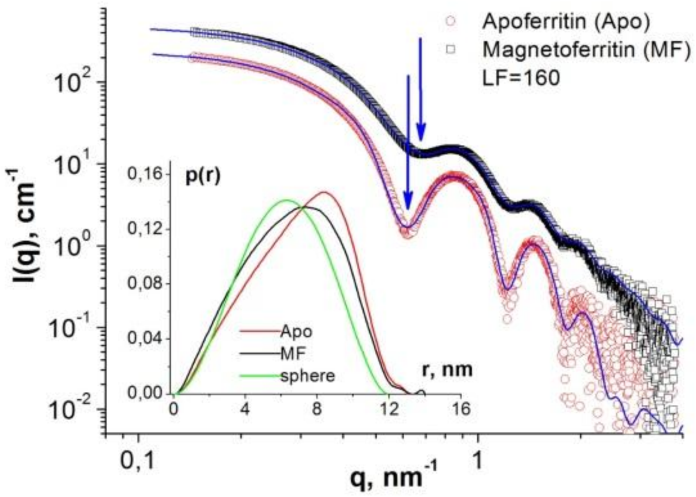
- **Magnetoferritin differs from the natural iron storage protein, ferritin, in the iron core composition of magnetic iron oxide phase (Fe_3O_4, γ-Fe_2O_3) surrounded by the protein shell – apoferritin with an outer diameter of about 12 nm.**
- **The drug binding to magnetoferritin allows visualization of pathological tissues or targeted transport directly only to the damaged area of the organism without the side effects of the drug on healthy tissues and organ .**
- **All these applications rely on the ability of magnetoferritin to pertain or to change its core–shell structure.**
- **SANS is an experimental method particularly suited to study the details of such core–shell type objects of sizes 10–20 nm. Contrast variation technique in SANS can be used to reveal fine details of dispersions of multicomponent particles and clusters in liquid media. The structure and interactions of magnetic or non-magnetic particles can be obtained by the polarized neutron scattering analysis.**

Interactions of Nanoparticles with Bio-Macromolecules

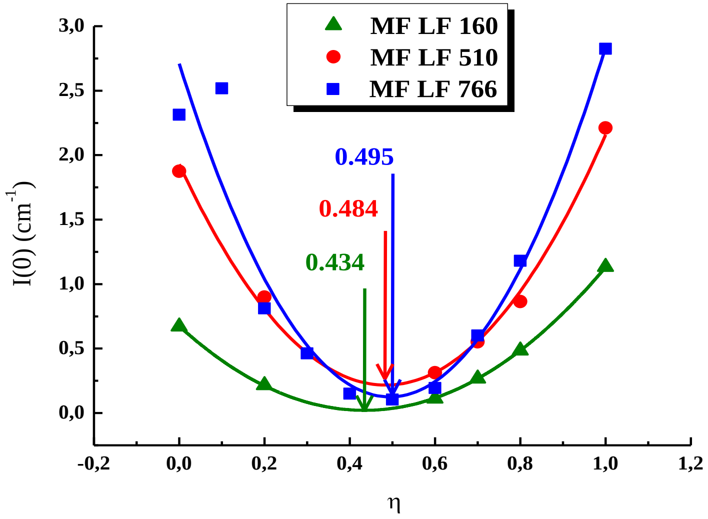
(FLNP JINR – Institute of Experimental Physics Slovak Academy of Science –Helmholtz-Zentrum Geesthacht – Kiev National University)

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





Destroy of amyloids

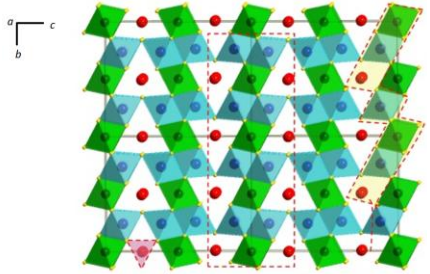


Instability of protein shell

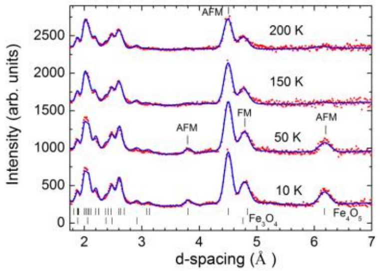
SAXS experiments indicate the destroying effect of Mfer on lysozyme amyloid fibrils with the effect increasing with the loading factor.

Novel type of the charge ordering state in iron oxide Fe_4O_5 involving competing dimer and trimer formation

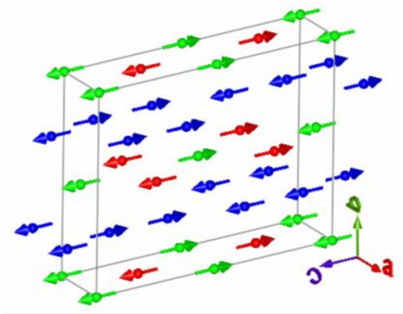
Previously known: Fe_3O_4, Fe_2O_3, FeO
A new one: Fe_4O_5



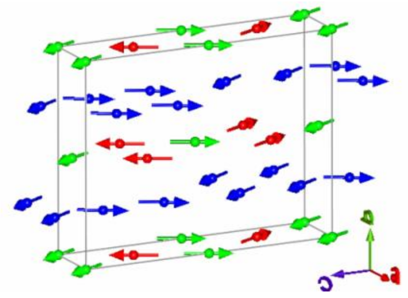
(a)



(b)

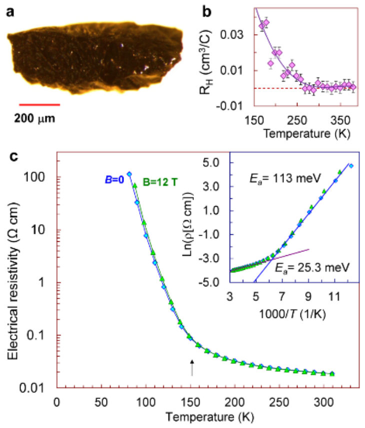


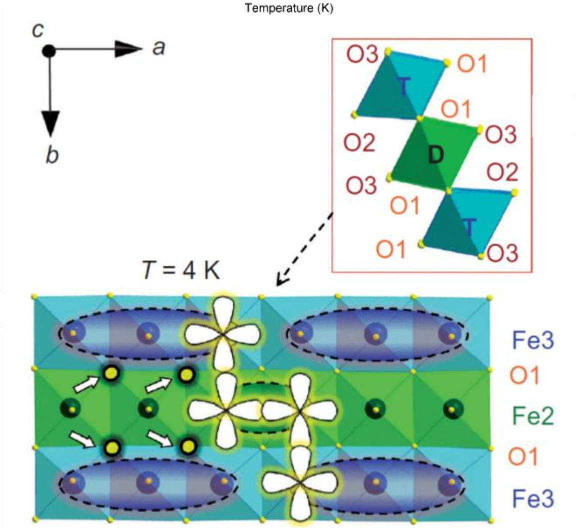
(c)



(d)

Crystal structure of Fe_4O_5 (a), neutron diffraction patterns, measured at different temperatures and processed by the Rietveld method (b), magnetic structures at T = 150 K (c), and T = 10 K (d).



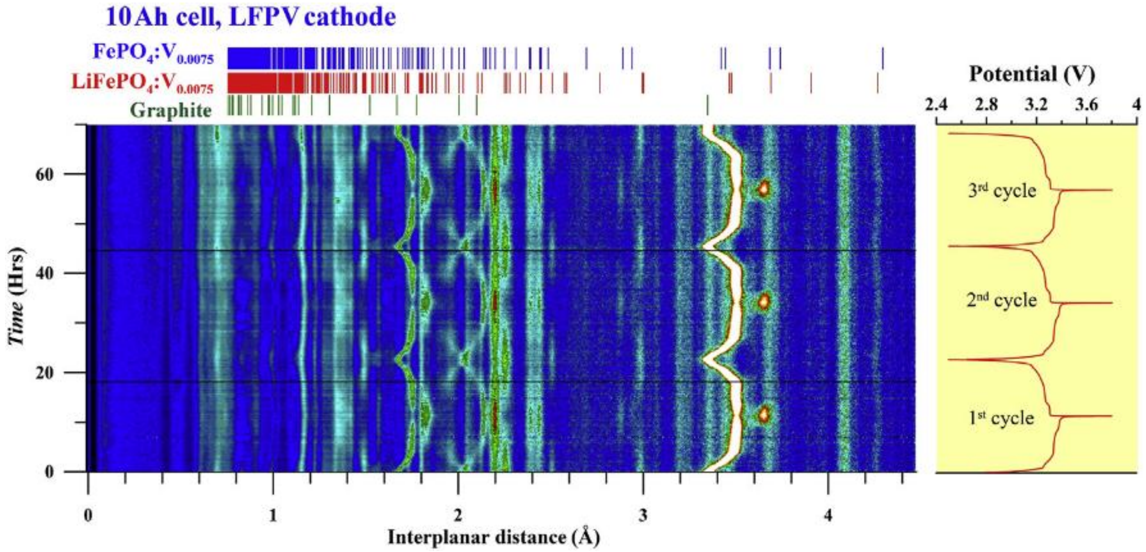


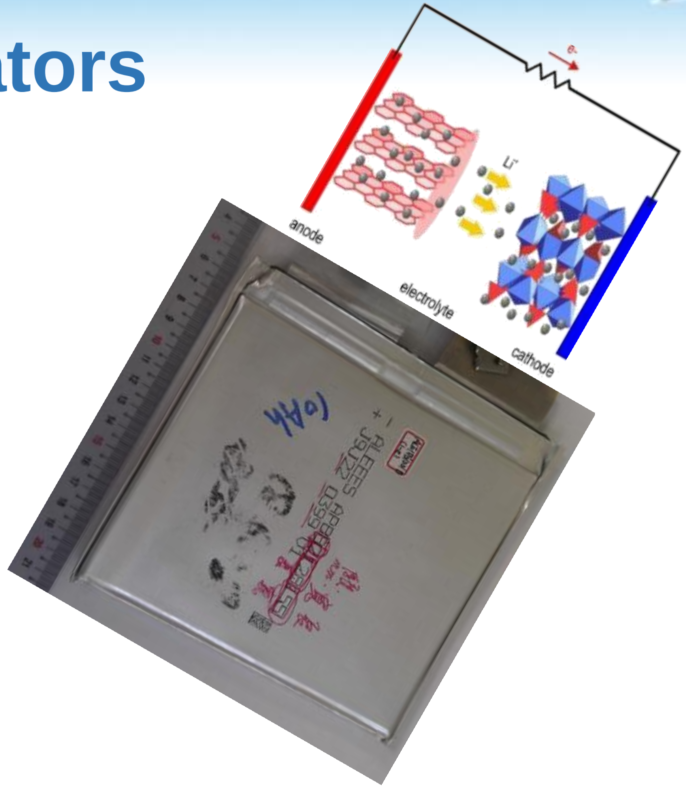
Formation mechanism of the dimeric and trimeric states

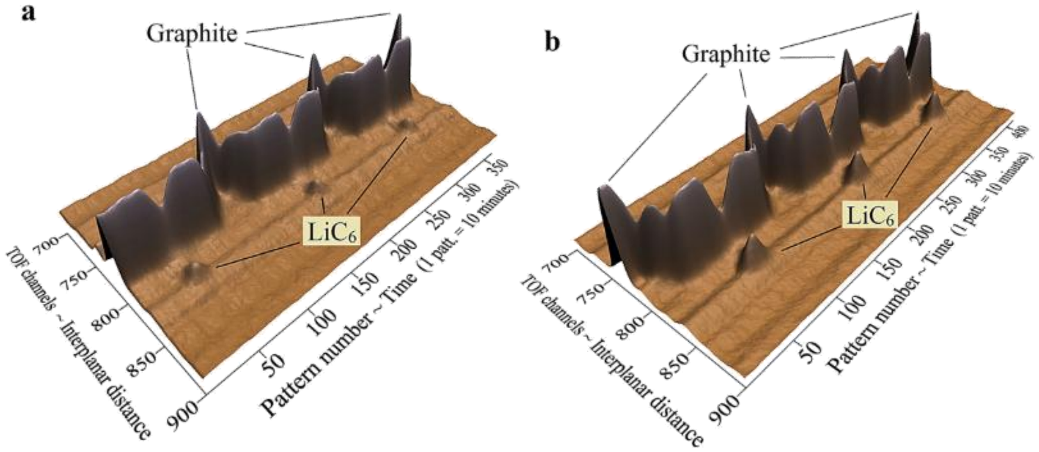
S.V.Ovsyannikov,.., D.P.Kozlenko, et al., Nature Chemistry (2016)

- Universität Bayreuth, Germany
- University of Augsburg, Germany
- National Institute of Chemical Physics and Biophysics, Estonia
- Institute of Metal Physics, RAS, Russia
- Institute for Solid State Chemistry, Russia
- University of Antwerp, Belgium
- European Synchrotron Radiation Facility, France
- Yanshan University, China
- Moscow State University

Diffraction Studies of Li-Based Accumulators

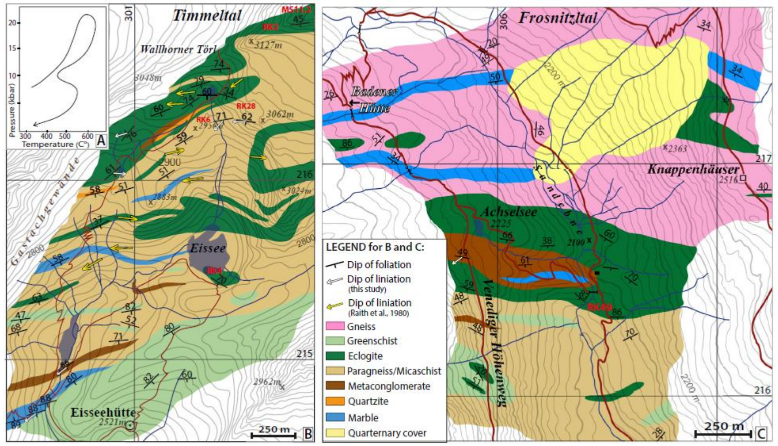




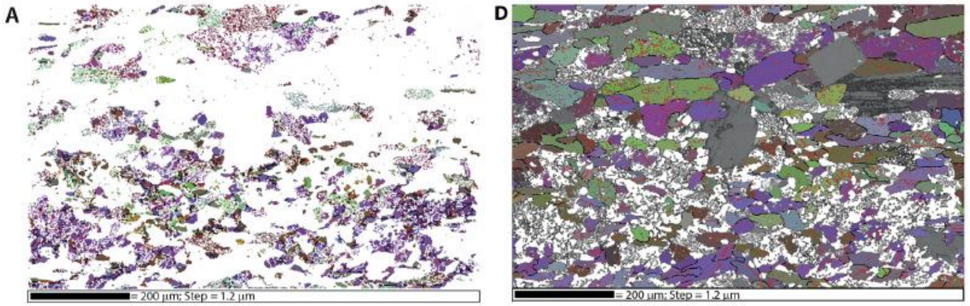


Real-time monitoring of transition processes during charge-discharge cycles revealed 10% increase of LiC_6 phase in anode when cathode was doped with vanadium oxide, which correlates with better electrochemical properties.

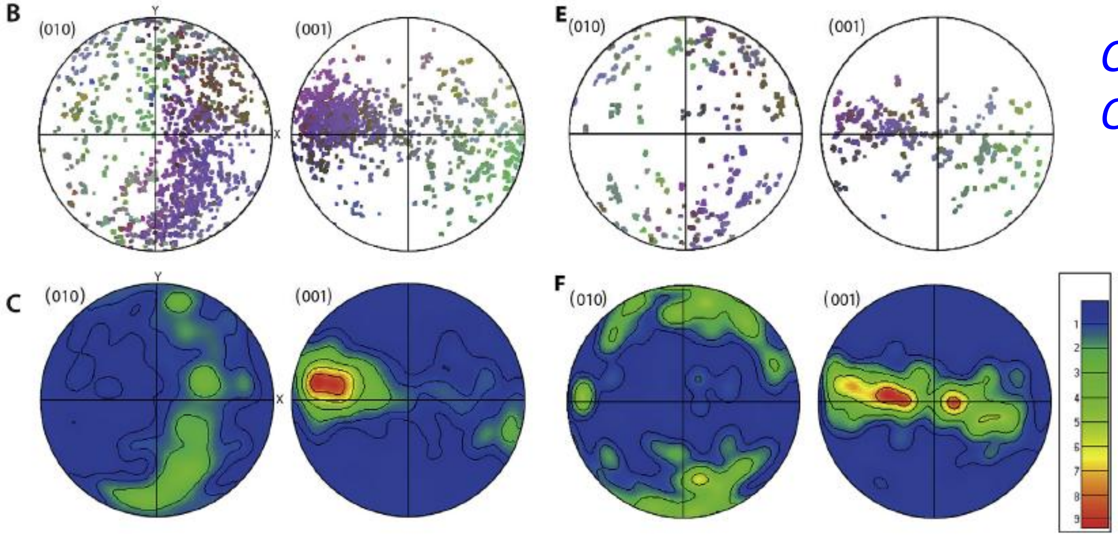
Deformation inside a paleosubduction channel – Insights from microstructures and crystallographic preferred orientations of eclogites and metasediments from the Tauern Window, Austria.



Geological location



Microstructural observations



Crystallographic preferred Orientation (texture)

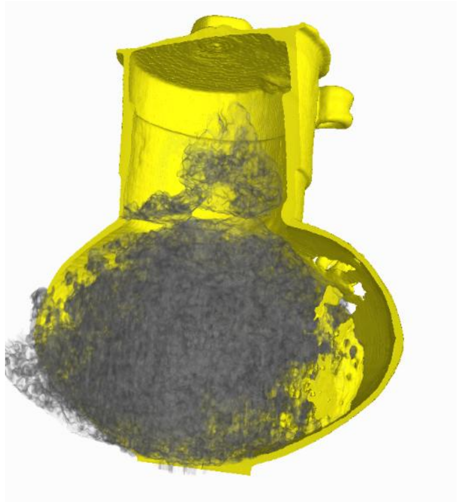
Keppler et al. (2016) J. Struct. Geol. **82**, 60-79.
[doi: 10.1016/j.jsg.2015.11.006]

Neutron radiography and tomography facility: cultural heritage studies

Institute of Archaeology of Russian Academy of Science

«Tver' treasure» was found in 2014

The part of Old-Russian ancient bracelet dated to XIV century (left) and neutron tomography reconstruction (right).

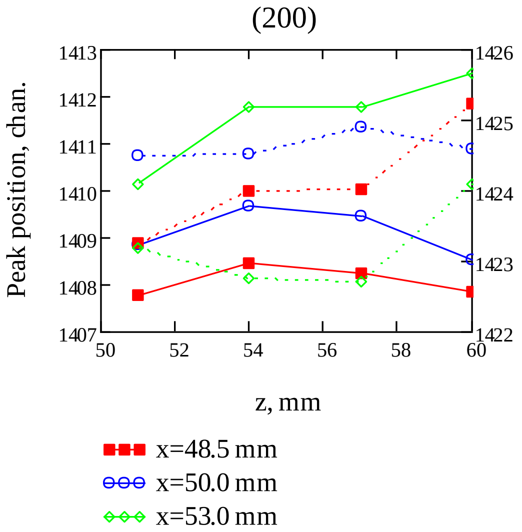


Gold Scythian jar (left) and neutron tomography reconstruction (right)

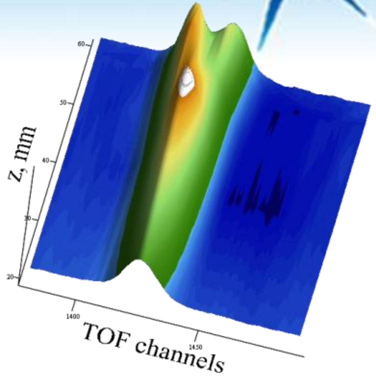
Fourier Stress Diffractometer

САТУРН
НАУЧНО-ПРОИЗВОДСТВЕННОЕ ОБЪЕДИНЕНИЕ

Ni-based super alloy single crystal turbine blade on FSD diffractometer. **NPO "Saturn"** (Rybinsk,Russia) – an aircraft engine manufacturer.

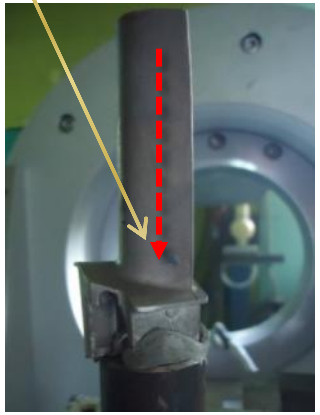


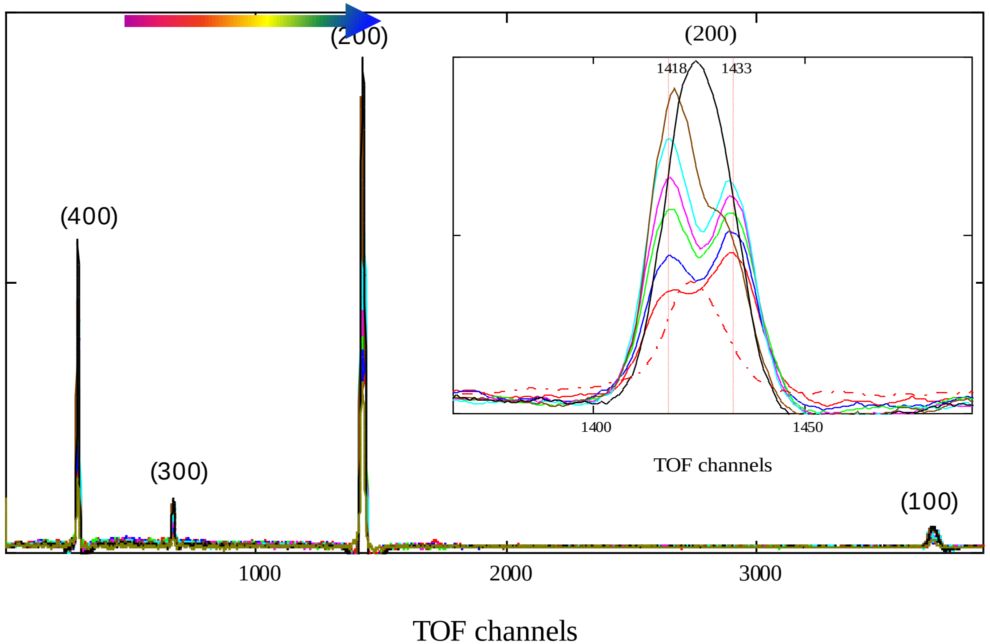
Diffraction peak (200) position vs. scan coordinate *z* in "parasitic" grain region



Top: 3D plot and map of the neutron diffraction pattern near (200) reflection during scan along *z* coordinate in the "parasitic" grain region.
Bottom: Total neutron diffraction pattern from single crystal turbine blade. The inset demonstrates (200) reflection shape evolution during z-scan.

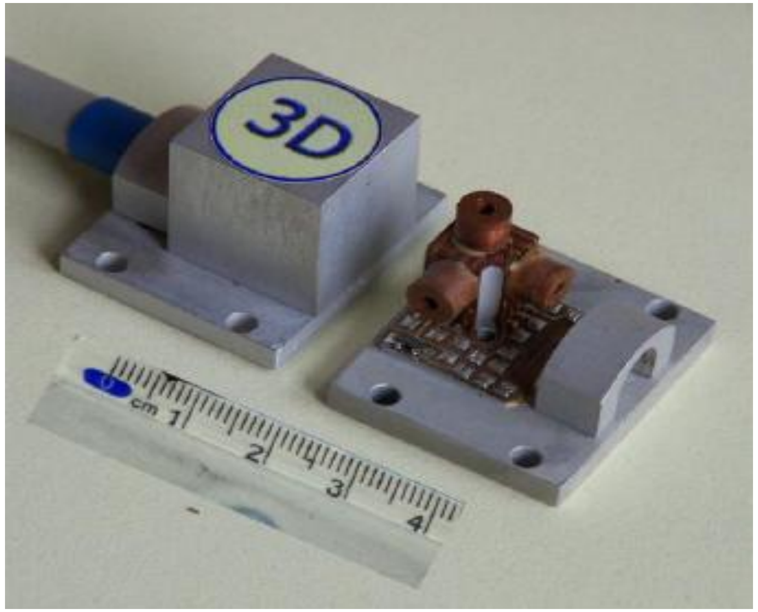
"Parasitic" grain





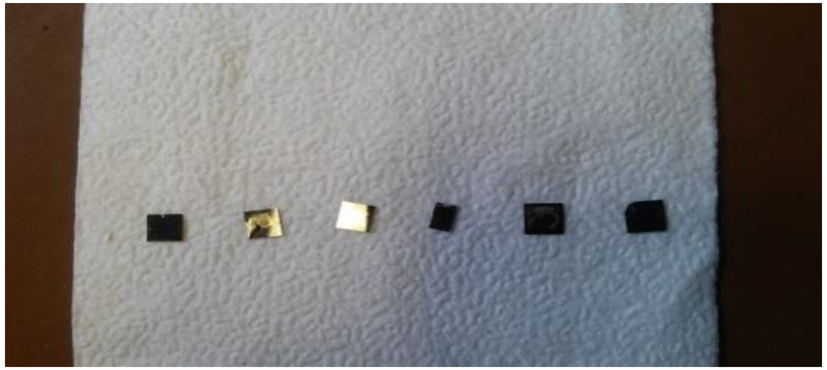
Research of the radiation resistance of 3D Hall magnetic sensors for ITER, DEMO and NICA

Neutron fluence ~ 10^{20} n/cm^2/s and sensors feel themselves very well



Experimental evaluation of stable long term operation of semiconductor magnetic sensors at ITER relevant environment / I. Bolshakova [et al.] // Nuclear Fusion. – 2015. – Vol. 55. – №8. – P. 083006-083016

Irradiation of a single crystal diamond sensors for ATLAS and CMS (LHC and HI-LHC)



a b

Radiation coloration of Topaz

Blue Topaz is a product of radiation technology, but they are most popular in jewelry.
In nature their deposits were depleted.

Metrology in Chemistry CHIMIA **2009**, *63*, No. 101

A Primary (Ratio) Method to Determine SI-Traceable Values of Element Content in Complex Samples

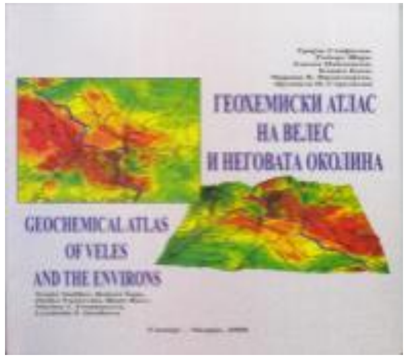
NAA

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	*V*	*Cr*	Mn	*Fe*	Co	*Ni*	Cu	*Zn*	Ga	Ge	*As*	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	*Cd*	In	Sn	Sb	Te	I	Xe
Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	*Pb*	Bi	Po	At	Rn
Fr	Ra	Ac**											Rf	Db	Sg	Bh	Hs
	*	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
	**	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lw		

Neutron Activation Analysis

…investigating the environment

Determination of a large number of potential pollutants in air and monitoring of their time and spatial distribution.



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

… studying the food stuffs

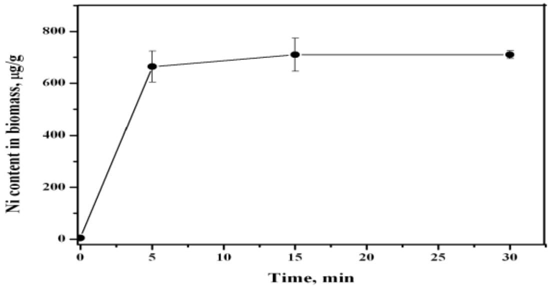
Determination of the elemental content in herbs and other food stuffs in order to assess the excess or the lack of some elements in samples.

The elemental content of major food stuffs is a major factor in human metabolism. The lack or excess of some microelements can induce some diseases.

The elemental content of herbs used in medicine and cosmetics can influence their benefit for health. The content of forages can influence the milk productivity and cattle health.

… cleaning our environment

Development of biological methods for waste water treatment is very important to reduce the secondary pollution with chemicals.

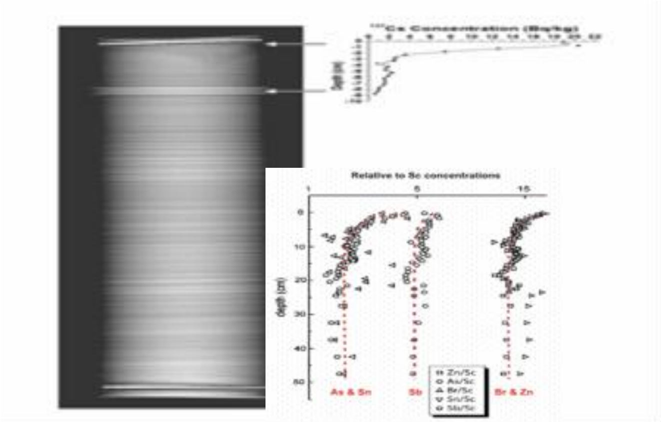


Study of nickel uptake by cyanobacteria Nostoc linckia from chemically complex wastewater effluent.

Neutron Activation Analysis

… understanding the Earth

The element content of geological samples can provide information on the Earth formation and evolution



Geochronology and retrospective pollution study of the deep sea sediments.

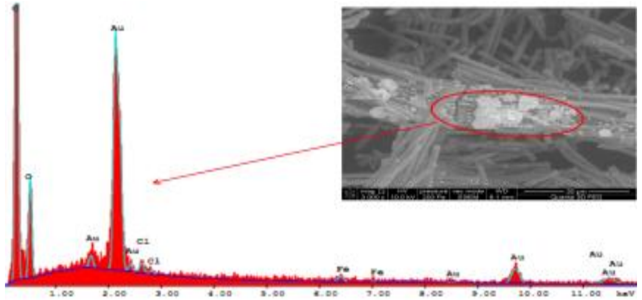
… learning about our past

Determination of the elemental composition of the artifacts can provide information on the development and interaction of different cultures or authenticity of the artifacts.

Obsidian is certainly the lithic material providing archaeologists with the clearest evidence of contact between different cultures.

… creating our future

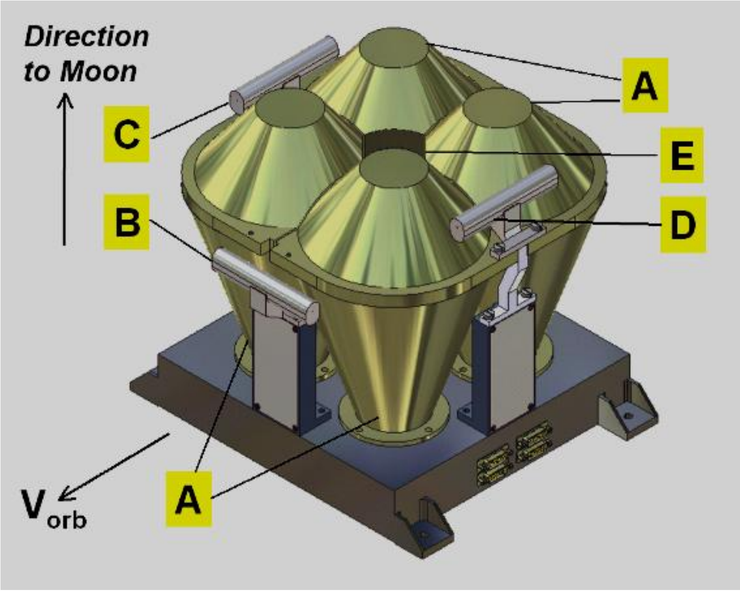
Monitoring of biosynthesis of Ag and Au nanoparticles by various microorganisms.

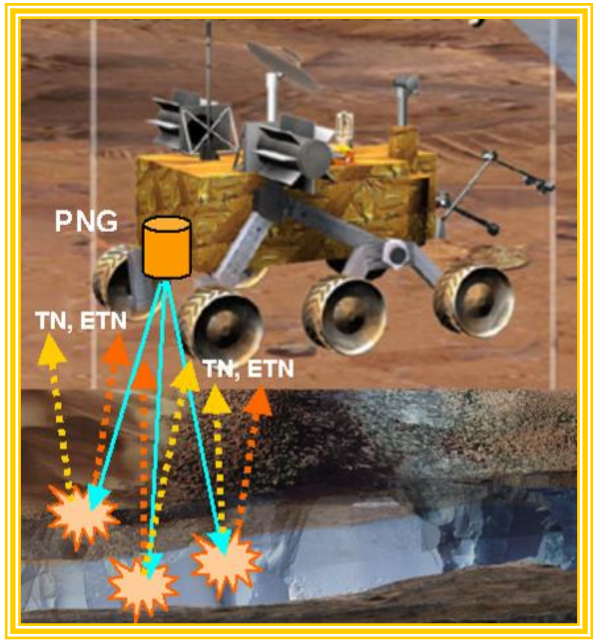


The resulting biomass containing nanoparticles of 10-80 nm can be used for both industrial and medical purposes.

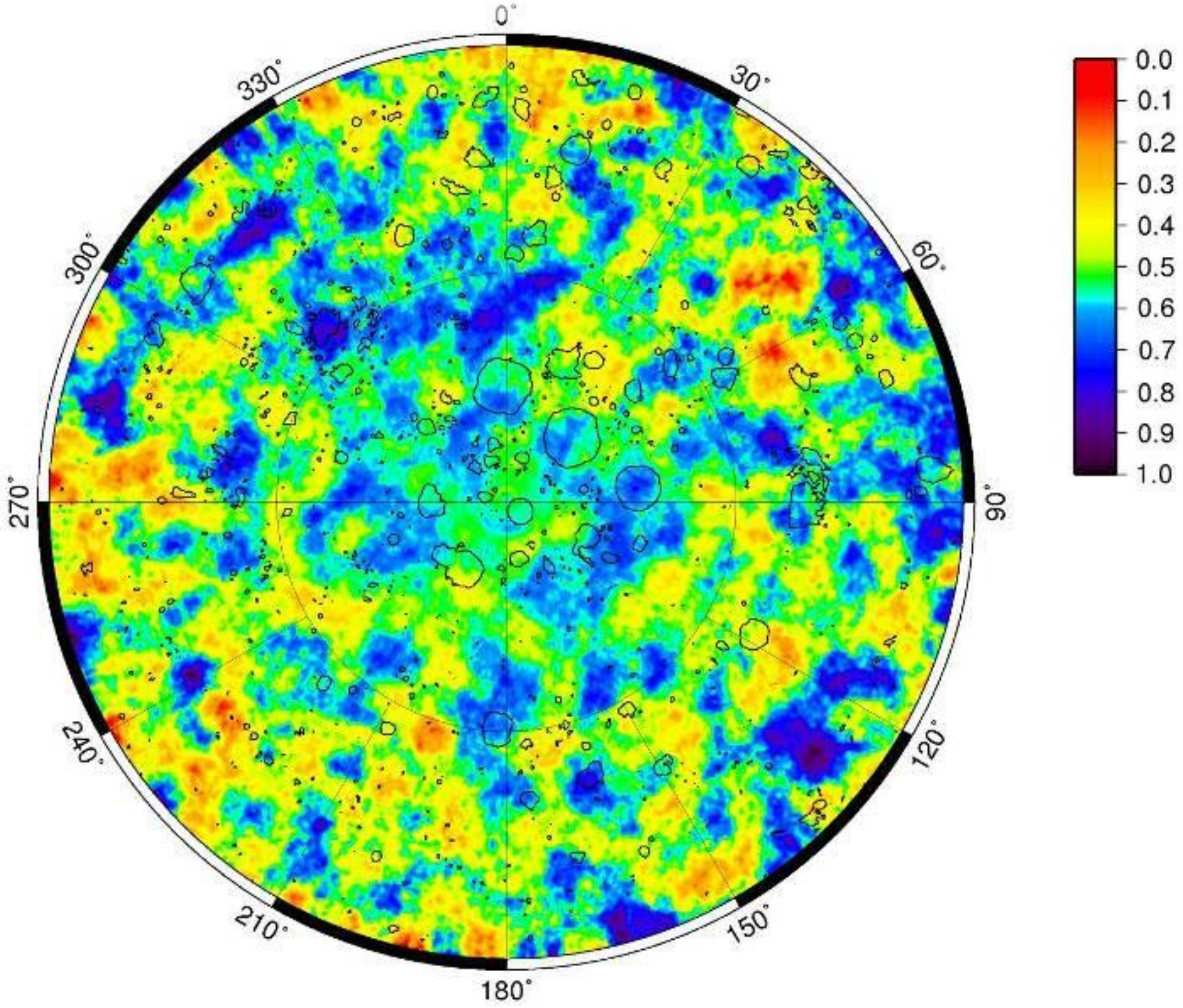
Development of the neutron and gamma detectors for spacecrafts

- Cooperation with Russian Space Research Institute since 1997;
- FLNP responsibility are: conceptual design, physical and numerical modeling, physical calibrations;





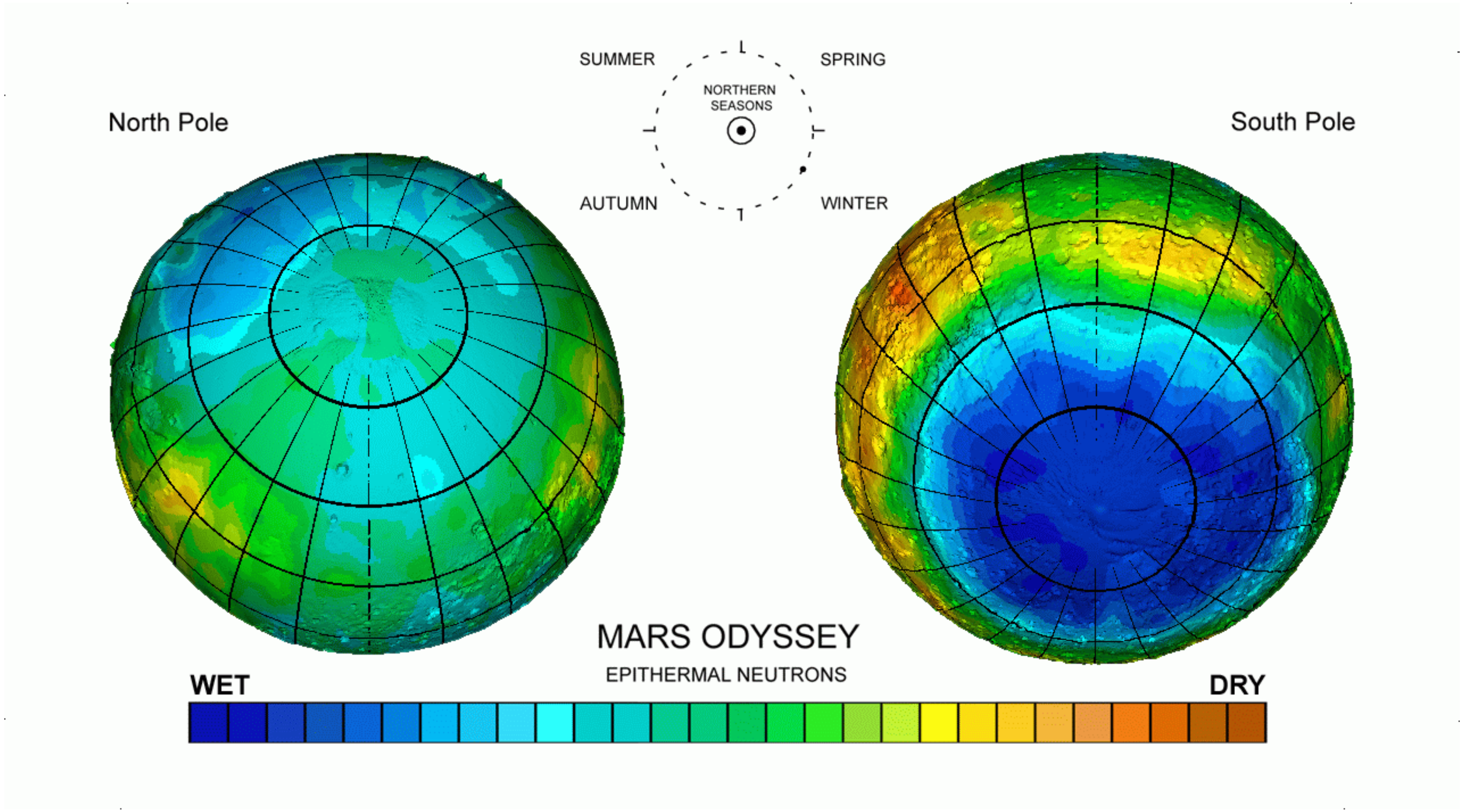
Lunar Exploration Neutron Detector (LEND)



First LEND results – blue colored regions indicates high (up to 20%) concentration of the hydrogen

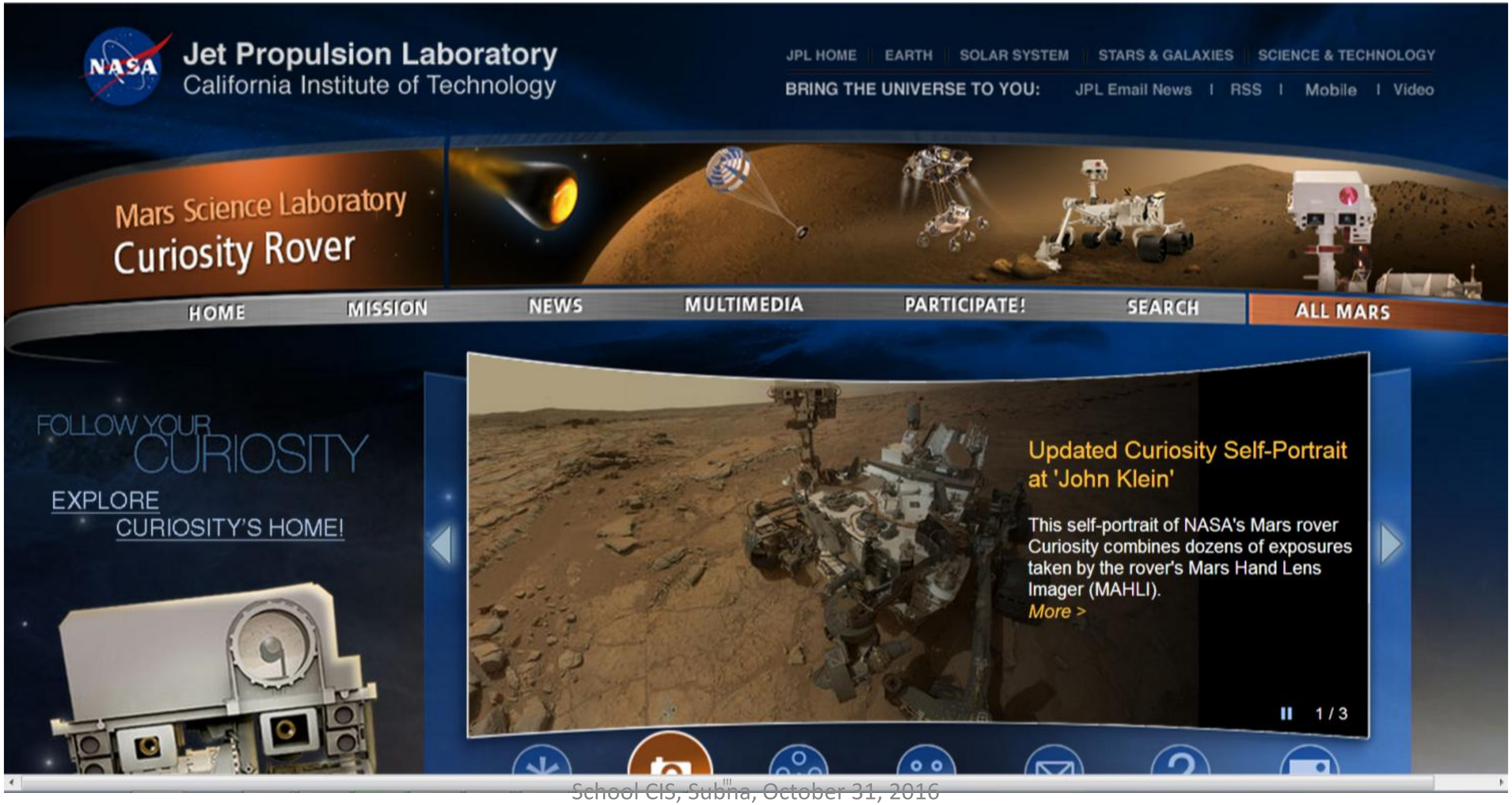
The map of the LEND inner sensors count rates. Difference between red and blue color – 10%

SEEKING WATER ON MARS

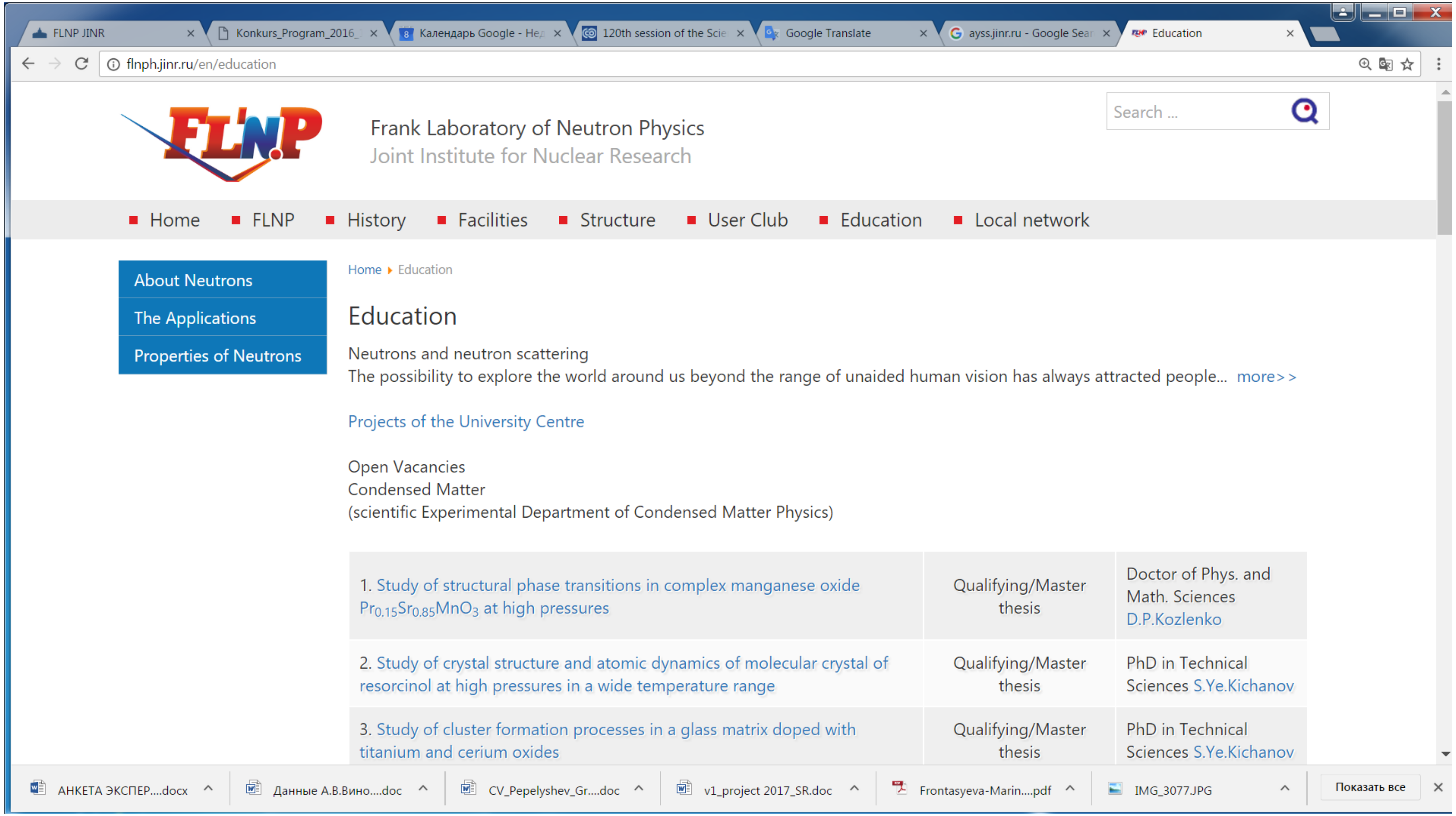


HEND has 4 signals of neutrons from sensors and for each of them the map of orbital measurements is currently produced.

Experiment DAN onboard Curiosity Rover



28 themes
Diploma work, master study and PhD study



Thank You!