Study of the radiation aging of materials with using of beam of the fast neutrons at BINP SB RAS

Viktor Bobrovnikov

v.s.bobrovnikov@inp.nsk.su

Budker Institute of Nuclear Physics SB RAS

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Novosibirsk State University
*THE REAL SCIENCE

Motivation

1. As part of a large-scale upgrade of the LHC (*LS3 2026–2029, Run4 2029–2033*), aimed at increasing its luminosity and energy, all four detectors operating at this collider are being modernized to work with high luminosity, including CMS detector (Compact Muon Solenoid)

2. Luminosity and energy of LHC beams will be increased $\Rightarrow$ radiation load on detector systems will be increased too

3. **Neutron irradiation** gives one of the main contributions to radiation damage. Fast neutrons with an energy of the order of MeV actually destroy the nuclei of materials

Novosibirsk CMS group

- NSU (Novosibirsk State University) is a member of the CMS collaboration $\Leftrightarrow$ laboratory of hadronic interaction physics
- Calibration of electromagnetic calorimeter of CMS detector is one of the tasks this group
- The Laser Monitoring system uses optical fibres to inject the light into crystals and reference pin diodes. Under the neutron flux, the fiber darkens due to the destruction of them structure, especially in areas close to the beams, where the radiation background is the biggest
- So, necessary to perform check **radiation resistance** of these materials under significant neutron fluence, up to $\mathbf{10^{14} neq/cm^2}$

! Only one question, where we can find such neutron fluence ?

Boron neutron capture therapy (BNCT) facility as source of the fast neutrons

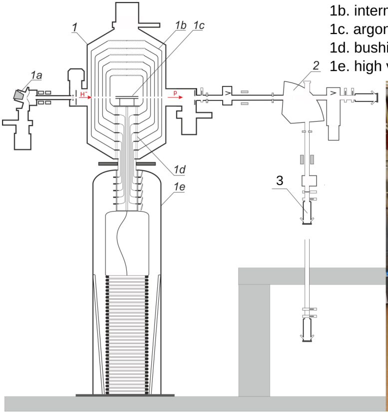
✓ Principle of BNCT: selective the destruction of malignant tumors by accumulation of a stable isotope boron-10 in them and subsequent irradiation with epithermal neutrons

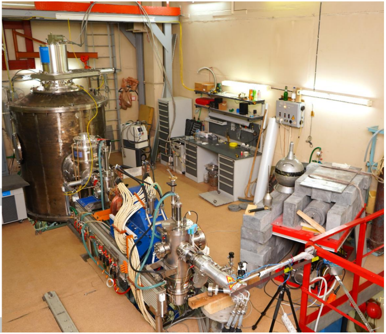
Main parameters of BNCT facility at BINP SB RAS

- Energy of proton beam 0.6 $\div$ 2.3 MeV, achieved stability and monochromaticity are at the level of 0.1%
- Beam current up to 3 (10) mA, stability 0.4%
- Generation of epithermal neutrons with an energy from 0.5 eV up to 10 keV (in process $p + {}^7Li \rightarrow {}^7Be + n$)

Scheme of the BNCT facility (named as VITA)

1. vacuum insulation tandem accelerator
 1a. source of negative ions hydrogen
 1b. intermediate electrode
 1c. argon target
 1d. bushing insulator
 1e. high voltage power supply
2. bending magnet
3. neutron producing target





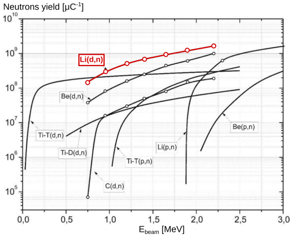
BNCT facility as source of the fast neutrons

- Hydrogen has been replaced with deuterium in the negative ion source
- Basic nuclear reactions due the interaction of a deuteron beam with lithium target

$$d + {}^{7}Li \rightarrow {}^{8}Be + n + 15.028 \text{ MeV}$$

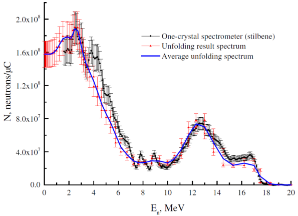
$$d + {}^{7}Li \rightarrow 2\,{}^{4}He + n + 15.122 \text{ MeV}$$

`Kononov V., Bokhovko M., Kononov O. Accelerator Based Neutron Sources for Medicine // Proc. of Intern. Symp. on Boron Neutron Capture Therapy. Novosibirsk, 2004`



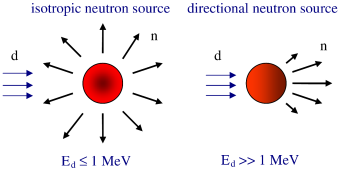
- Neutrons energy distribution

`K. Mitrofanov et al. The energy spectrum of neutrons from 7Li(d,n)8Be reaction at deuteron energy 2.9MeV, EPJ Web of Conferences 146, 11041 (2017)`



- Angular distribution of neutrons

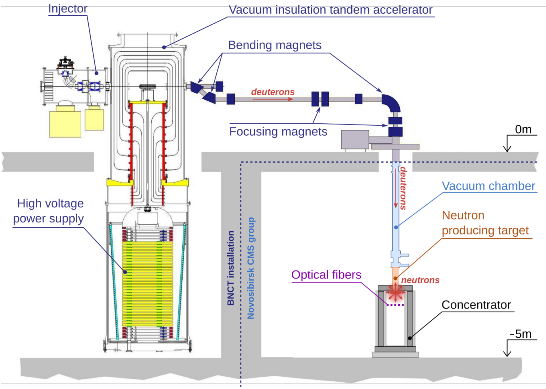
`Neutron production from 7Li(d,xn) nuclear fusion reactions driven by high-intensity laser-target interactions, Published 19 March 2010, Plasma Physics and Controlled Fusion, Volume 52, Number 4`



Peculiarities of the experiment with such power fast neutron fluxes

- Estimation of the dose in generation zone gives value of several tens of Sv/h (*lethal dose > 15 Sv*)
- In order to ensure necessary safety, neutrons are generated at underground 4 meters in room, walls and ceiling which were covered with shielding polyethylene (`NEUTROSTOP C3`)

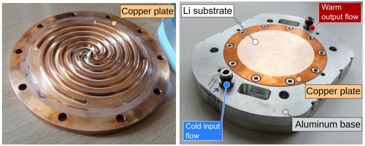
Experimental setup



✓ Set of special studies was carried out on the residual activation of various materials to test possibility of their using in the concentrator construction and target

- Concentrator design – only wood for inner and outside frames without using of any nails, special plumbum with small amount of admixtures
- Target design – aluminium alloys were used for housing and screws

Neutron producing target



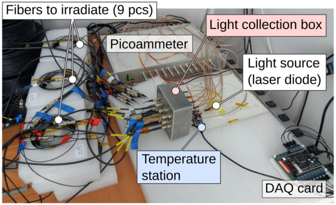
- Li substrate: thickness 100 mkm, diameter 90 mm
- 9 thermo sensors are located inside for determining position of beam
- water cooling system is necessary part of such kind of device

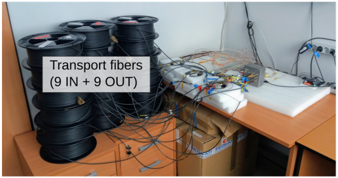
Lead concentrator

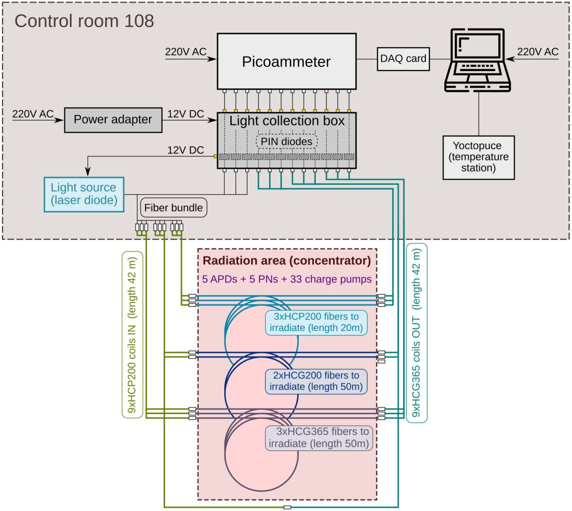
- purpose – first level protection (generation of fast neutrons is performed inside) and raising efficiency of irradiation (part of neutrons are reflected from walls and then are used again)
- inner dimensions 350 × 350 × 1000 mm
- thickness of lead is 100 mm (walls, bottom and top)

Experimental setup: scheme of the test

- Measuring equipment and materials were provided by the Saclay team
  - equipment: laptop, picoammeter, light collection box, light source and so on
  - materials: transport fibers (9 IN + 9 OUT), fibers to irradiate (HCP200, HCG365 and HCG200) and some items from ATLAS detector (APDs, PN diodes and charge pumps – passive material without any readout)







- One coil HCG200-50-2 was excluded from the experiment. Instead of it the direct connection between transport fibers was used. It was done to estimate level of possible degradation all transport fibers

Experimental setup: simulation

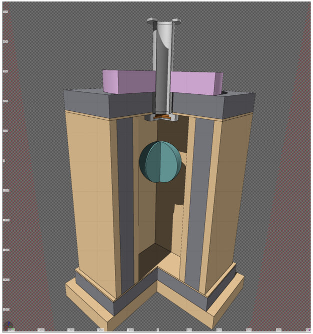
Direct measurement of the neutron flux (neq/cm2) is impossible due to high doses of the order of 100 Sv/h, at least we do not know such devices which can operating under such conditions.

✓ FLUKA package (`http://www.fluka.org/fluka.php`) was used for calculation of neutron flux

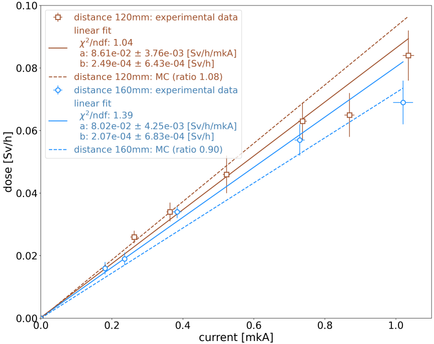
Experimental verification of the simulation

- Special device for detection of slow neutrons (UDMN−100) was placed directly inside the concentrator for measuring **ambient dose rate equivalent** of neutron radiation $H^*(10)$
- Measurements of dose were performed under target with small beam current $\simeq$1 mkA due to the limitation associated with the level of the maximum dose measured by UDMN−100 which is 0.1 Sv/h (working current is more than 1000 times)

Example description of geometry



Comparision of simulation with experiment

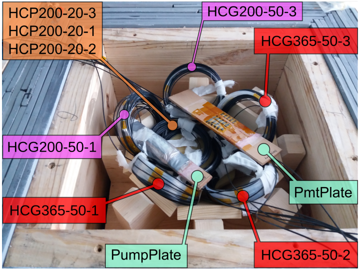


✓ The difference between experimental data and simulation results is around 10%

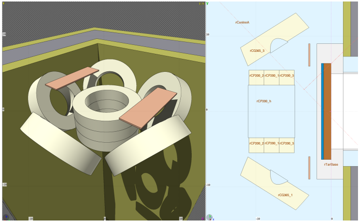
Experimental setup: calculation of neutrons fluence (neq/cm^2)

- Average fluence neq/cm^2 was calculated for all irradiated fibers (8 pcs), for plates with SiPM and charge pumps too
- Scheme the disposition of investigated objects

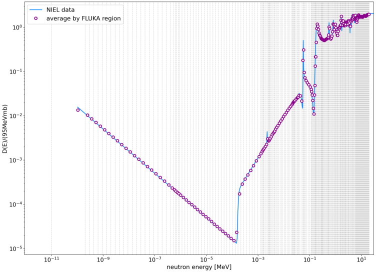
In experiment



From simulation



- Simulation results: $E_d = 1.5$ MeV and $I_d = 1.0$ mA

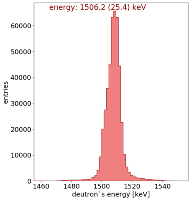


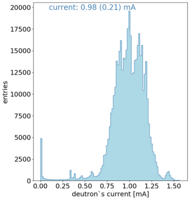
A.Vasilescu and G.Lindstroem Displacement damage in Silicon, http://sesam.desy.de/~gunnar/Si-dfuncs

Object	$10^8 \times$neq/cm^2/sec
HCP200−20−1	3.31
HCP200−20−2	2.24
HCP200−20−3	5.39
HCG365−50−1	1.40
HCG365−50−2	2.31
HCG365−50−3	2.58
HCG200−50−1	1.23
HCG200−50−3	1.58
PmtPlate	4.57
PumpPlate	1.31

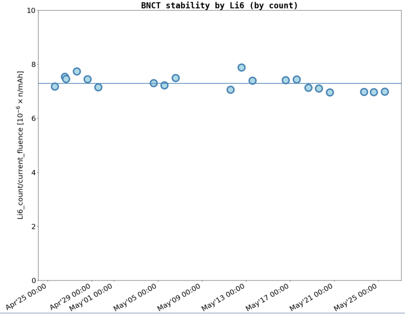
Experiment: VITA parameters during the irradiation

- Duration of the irradiation test – one month (25/04/2022 – 25/05/2022), 18 daily shifts per 7–8 hours
- Parameters deutron beam: energy 1.5 MeV, current 1.0 mA

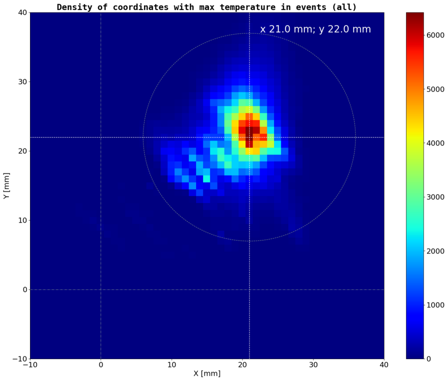




- Stability of fast neutron generation was measured by detector with GS20 scintillator by Saint-Gobain production. The detector was located at 3 m distance from concentrator.

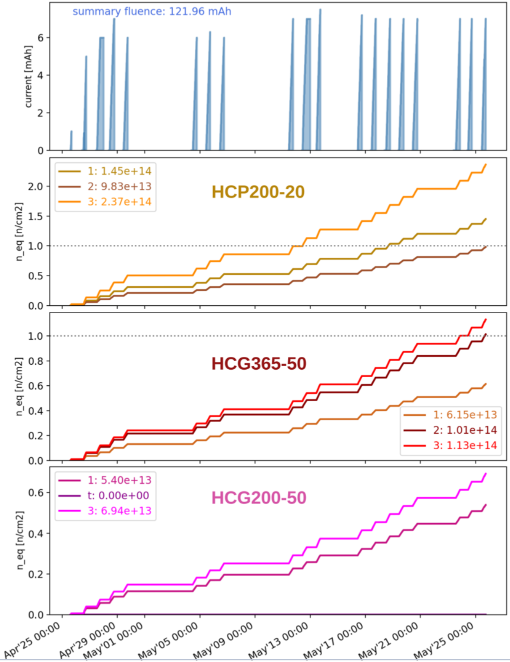


- The position of deutron beam was shifted relative to center of concentrator (x=21 mm, y=22 mm)

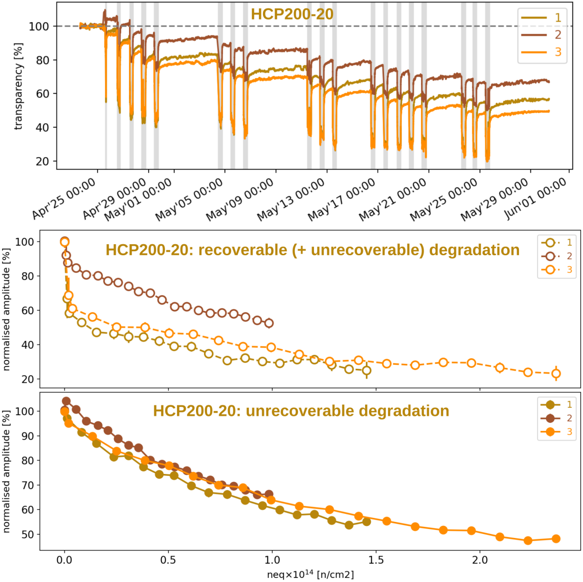


✓ The difference was taken into account to calculation of neutron flux through each coil fiber

Experiment: rate of dose accumulation



Experiment: example degradation of trancperency for HCP200−20 fibers



Results of the radiation aging of optical fibers

- The degradation of transparency at level from 20% to 35% (over the full length of the fibres) was obtained for a fluence of 10^{14} neq/cm^2

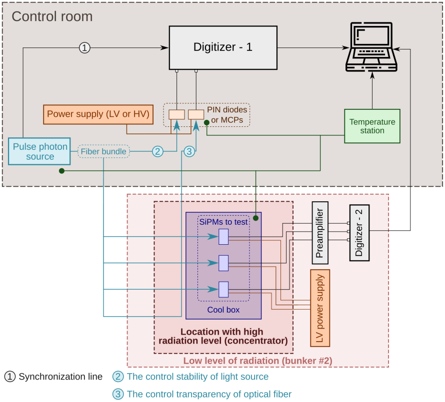
	HCP200 (20 m length)			HCG365 (50 m length)			HCG200 (50 m length)		
	3	1	2	3	2	1	3	t	1
ⓐ $10^{14} \times n_{eq}/cm^2$	2.37	1.45	0.98	1.13	1.02	0.61	0.69	$\simeq$0	0.54
ⓑ degradation [%]	−51.4	−44.3	−34.4	−22.4	−23.6	−18.2	−14.3	2.5	−11.7
ⓑ/ⓐ/length	−1.1	−0.6	−0.7	−1.0	−0.5	−0.6	−1.0	—	−0.4

- Such a drop in the amplitude of the calibration signal can be restored by increasing amplitude level of source light. So, team of calibration of calorimeter CMS detector is happy
- Neutron flux neq/cm^2 through SiPM and DC/DC convertors is 2.01×10^{14} and 0.57×10^{14}, respectively
- The rapid degradation (beam is ON) and rapid recovery (beam is OFF) of transparency was observed

New stand for testing of SiPM

✓ Next task for our group is developing stand to investigate behaviour of SiPM under irradiation

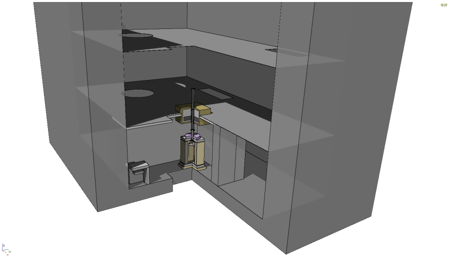
- Principal scheme of the stand



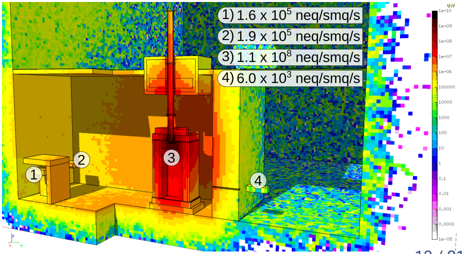
- One of the important question is placement of equipment relative to the concentrator (location to generate fast neutrons)
- Acceptable level of dose is up to 10^6 neq/cmq/s ⇔ info from CAEN

- Estimate of dose level via FLUKA

Example description of geometry of bunker #2



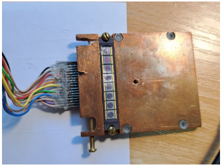
Simulation results ($E_d = 1.5\,\mathrm{MeV}, I_d = 1\,\mathrm{mA}, t = 1\,\mathrm{s}$)



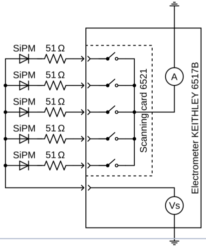
New stand for testing of SiPM: status of readout system and the first results

Keithley electrometer 6517B

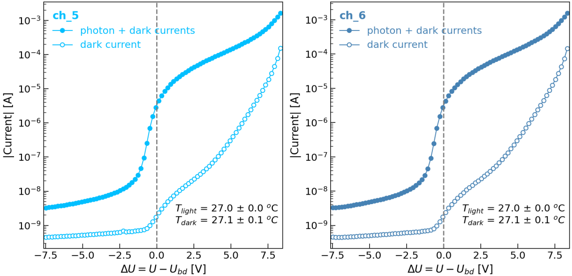
SiPMs by Hamamatsu for the CMS HCAL phase I upgrade



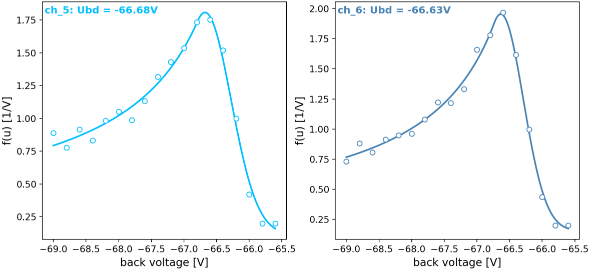
SiPMs readout scheme



Example of IV characteristic (two SiPM)

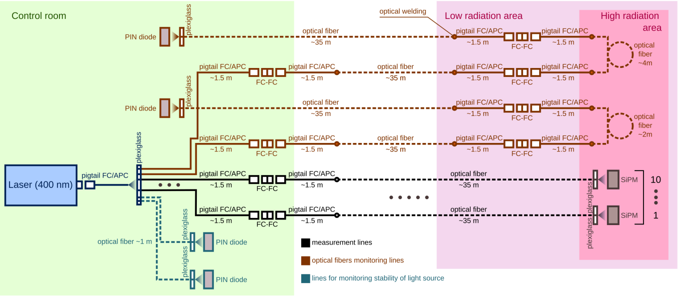


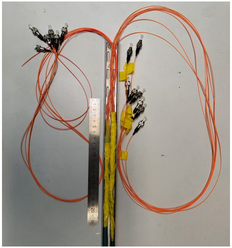
U_{bd} was calculated as maximum of function $f(U) = \frac{1}{I}\frac{dI}{dU}$



New stand for testing of SiPM: current status of other hardware

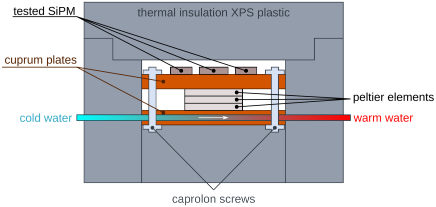
Principal scheme of light system (left) and example of realised fiber bundle (right)



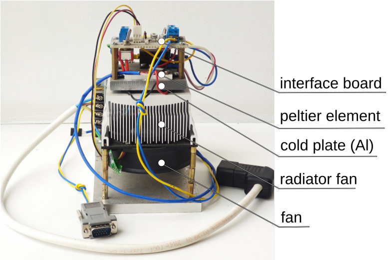


Camera cold and heat: temperature range from -20°C to $+40^\circ$C, accuracy about 0.1°C

Sketch of the camera



Camera prototype with air cooling



Conclusion

- BNCT facility at BINP SB RAS provides irradiation the dose at level **10^{14} neq/cm^{2}** (in the case of continuous generation, the time will be about 110 hours), this is quite enough to check the radiation resistance of materials, which are proposed to use in the HEP projects
- The uniqueness of this radiation tests in contrast to irradiation in reactor is the precise control of the accumulated dose with continuous measuring of degradation fiber transparency
- It has been demonstrated for the first time that at the BINP SB RAS it is possible to operate with such doses using of neutron beam
- It could be in further used for the wide range of radiation test tasks, related with the development of facilities for HEP

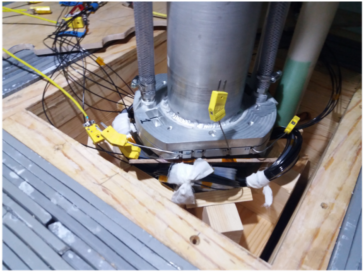
Our plans

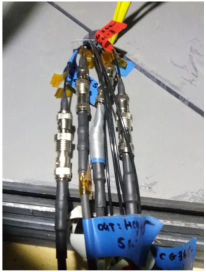
- Modernization of the BNCT facility to increase the dose:
  - new bending magnet to operate with deuteron beam more high energy 2.2 MeV (now 1.5 MeV)
  - increasing deuteron beam current up to 5 mA (now 1 mA)
- We are developing new stand on base BNCT facility dedicated to perform investigation irradiation damage of SiPM and **we hope to get on beam in November 2023**

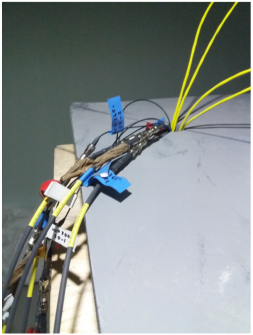
We open to new collaborations and you are welcome to Siberia to perform irradiation tests !

Backup

Experimental setup: placement of materials and equipments to test







Neutrons classification by energy

- Detailed scale

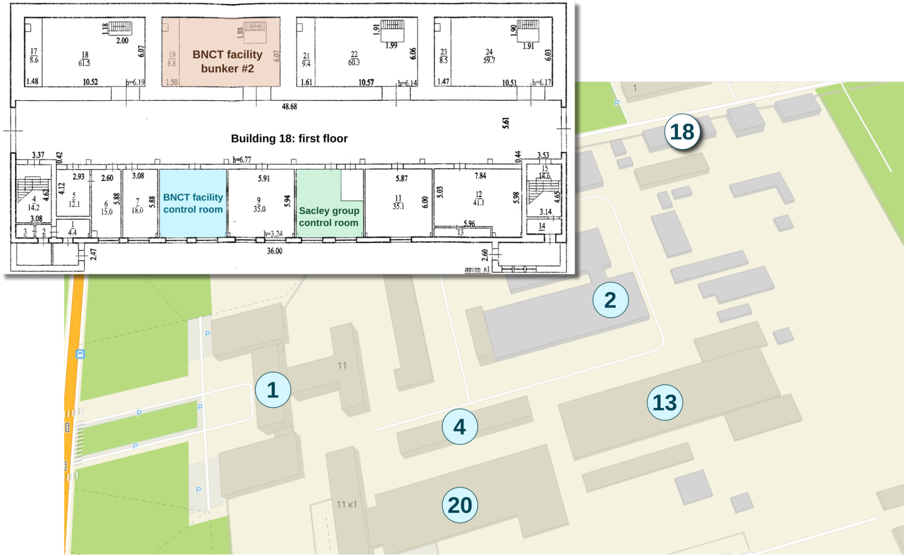
Cold neutrons	0 – 0.025 eV
Thermal neutrons	$\simeq$ 0.025 eV
Epithermal neutrons	0.025 – 0.4 eV
Cadmium neutrons	0.4 – 0.5 eV
Epicadmium neutrons	0.5 – 1 eV
Slow neutrons	1 – 10 eV
Resonance neutrons	10 – 300 eV
Intermediate neutrons	300 eV – 1 MeV
Fast neutrons	1 – 20 MeV
Relativistic neutrons	> 20 MeV

- Rough scale

Thermal neutrons	0.025 – 1eV
Resonance neutrons	1 eV – 1 keV
Fast neutrons	1 keV – 10 MeV

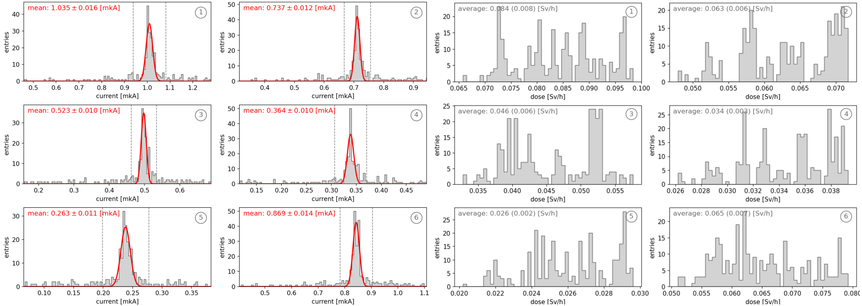
BNCT facility as source of the fast neutrons

- BNCT facility layout: control room, experimental area, offices



Experimental verification of the simulation: doses vs currents

First scan: distance between UDMN-100 and top of the concentrator is 120 mm



Second scan: distance between UDMN-100 and top of the concentrator is 160 mm