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

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Content

1. Introduction

Effects of radiation aging of SiPMs

Surface damage

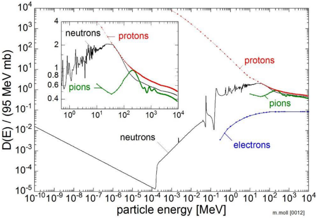
- Caused by ionization losses under the influence of X-rays with energies below 300 keV
- Occur primarily in the anti-reflective coating and the first layer of the semiconductor
- It leads to small increase in dark current

Damage to the crystal structure due to

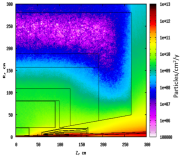
- Gammas, electrons, and positrons with energies great then of 300 keV
- Protons or neutrons, with an integrated flux of up to 10^{12} particles/cm^2 cause moderate damage; above 10^{12} particles/cm^2 damage is significant
- It leads to significant increase in dark current

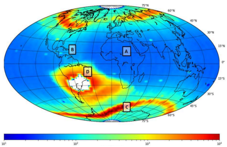
Restore

- Partial restoration of properties is possible through annealing
- This effect is due to the rearrangement of displaced atoms in the lattice



	Dose [neq/cm^2]
CMS (LHC)	6×10^{13}@HCAL@$300fb^{-1}$
Belle-II (SuperKEKB)	10^{12}@$70ab^{-1}$
ScTau (Novosibirsk)	10^{11}@VD, DC@1 year
Space	1.3×10^{8}@4 months on orbit of ISS 1.2×10^{10}@6 years on orbit 550 km



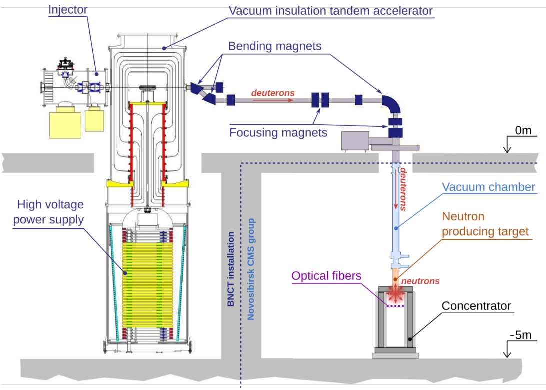


SiPM radiation workshop (25 – 29/04/2022, CERN)

- Initial and final radiation doses: $10^7 \div 2 \times 10^{12}$ neq/cm^2 and $6 \times 10^{11} \div 5 \times 10^{13}$ neq/cm^2

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

Scheme of the facility

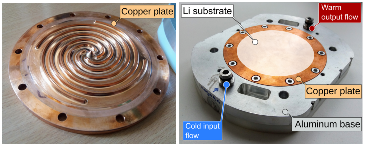


- To produce of deutron beam hydrogen has been replaced with deuterium in the negative ion source
- Basic nuclear reactions due the interaction of a deuteron beam with lithium target

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

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

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)

Calculation of neutron flux

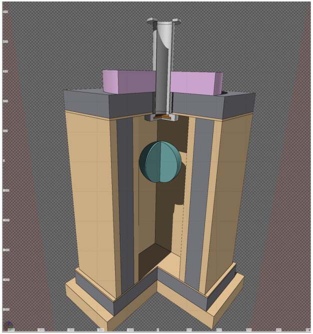
Direct measurement of the neutron flux (neq/cm2) is impossible due to high doses of the order of 100 Sv/h, at least we do not know such devices which can operating under such conditions.

FLUKA package was used for calculation of neutron flux

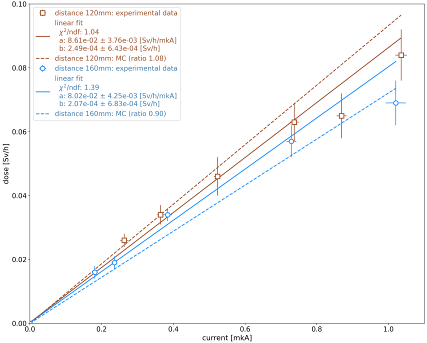
Experimental verification of the simulation

- 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 ≃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%

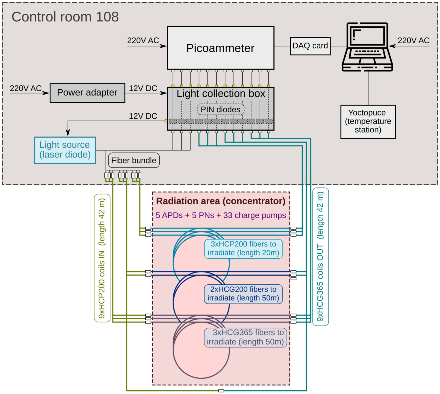
2. Irradiation tests

Optical fibers to CMS detector

- The Laser Monitoring system of electromagnetic calorimeter of CMS detector 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. Luminosity and energy of LHC beams will be increased ⇒ radiation load on detector systems will be increased too
- Novosibrsk group (NSU) was a member of the CMS collaboration ⟺ laboratory of hadronic interaction physics, so it is reason to perform such kind of investigation at BINP

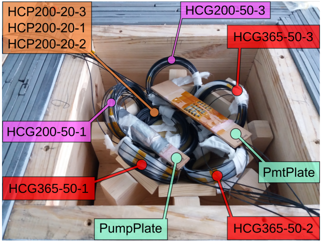
Scheme of the test

- Measuring equipment and materials were provided by the Saclay team

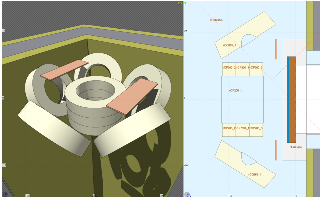


Layout the disposition of investigated fibers

In experiment

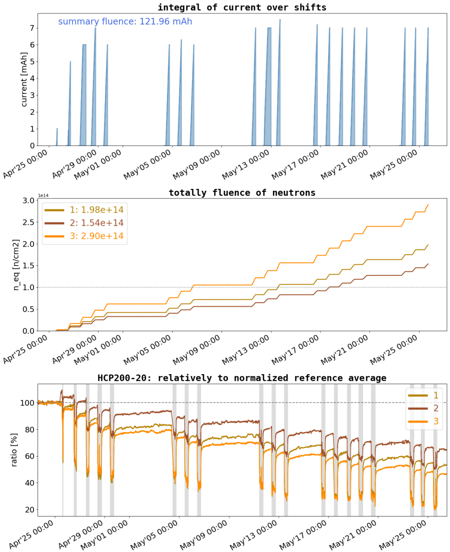


In simulation (to estimate fluence neq/cmq)



Optical fibers to CMS detector: results

Example degradation of transparency for HCP200–20 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
- Such a drop in the amplitude of the calibration signal can be restored by increasing amplitude level of source light
- Also, since such level of dose will be obtained at CMS within an estimated period of 3 to 5 years, the results obtained are fully satisfactory to the CMS team

> ✓ It was our first irradiation experiment at BNCT, it gave two main statements
>
> - BNCT facility at BINP SB RAS provides irradiation the dose at level 10^{14} **neq/cm^2** (in 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

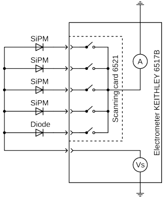
- The program investigation together with CMS team was planned for many years in advance. Unfortunately, the cooperation was stopped
- In 2023 we began developing a stand to study the radiation aging of SiPMs

Prototype of stand to investigate aging of SiPMs

- There are three main parts: climatic chamber, light distribution system and DAQ

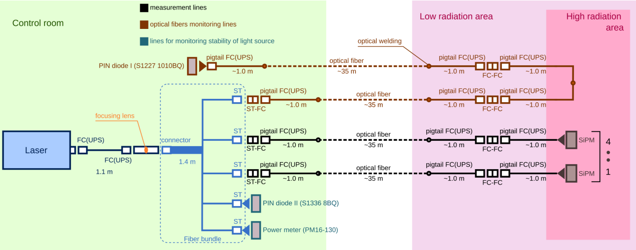
DAQ based on Keithley electrometer 6517B

- Scan card 6521 provides up to 10 channels
- Standard RS−232 is used to link with PC (SCPI command language)
- SiPMs scheme connection



Light distribution system

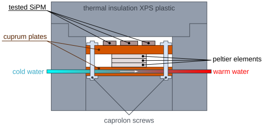
- Light source is laser MCLS1 (ThorLabs)
  - $\lambda = 640$ nm is used
- 4 lines to investigation of SiPMs
- 2 lines to monitor stability of laser
- 1 line to check optical transparency of transport optical fiber

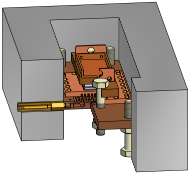


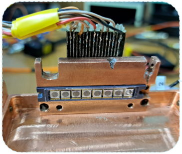
Prototype of stand to investigate aging of SiPMs

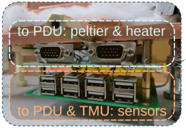
Climatic chamber

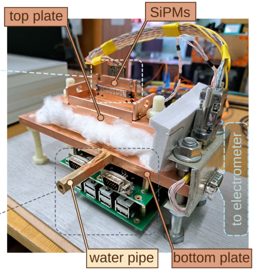
- Based on Peltier element with external cooling loop and set of heaters
- One temperature sensor is located close to the SiPMs in order to provide feedback, and six additional sensors are placed in various locations on the stand to monitor temperature
- Automatic feedback (temperature sensor → power of Peltier element or heaters) ensures fast and accurate control of the heating and cooling process, without the need for any software cycle

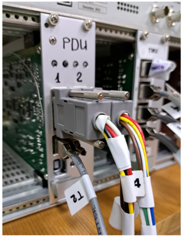












- The achieved accuracy of temperature setting and stability are $\pm 0.06°C$
- Obtained temperature range is from $-10°C$ to $+55°C$

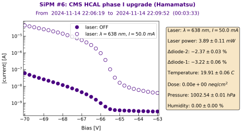
We conducted testing run in November 2024 using SiPMs from Hamamatsu. These were designed in 2012 for the HCAL of the CMS (phase I upgrade)

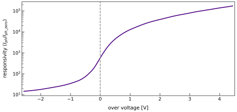
- amount of tested SiPMs – 4
- photocathode diameter – 2.8 mm
- cell size – 15 mkm
- number of cells $N_{cell} = 2.75 \times 10^4$
- quench resistance $R_q = 1.2$ MΩ
- $PDE = 400 \div 800$ nm (420 nm edge), $PDE_{max} \simeq 36\%$@475 nm

Prototype of stand to investigate aging of SiPMs

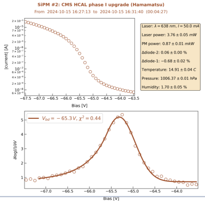
What we can measure using I – V curve only ?

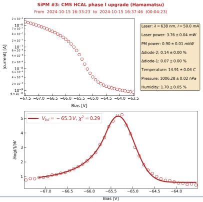
1. Linearity (photosensitivity) $\Leftrightarrow I_{photo}/I_{photo\_0}$, where:
   - I_{photo} – current in geiger mode ($V_{bias} \geq V_{bd}$)
   - I_{photo_0} – current in doide mode ($V_{bias} \simeq 0$)
   - and $I_{photo} = I_{light} - I_{dark}$



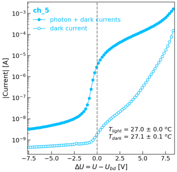


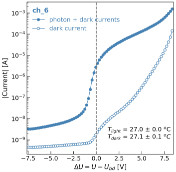
2. Breakdown voltage $V_{bd} \Leftrightarrow$ peak position of $LD = \partial log(I) / \partial V_{bias}$



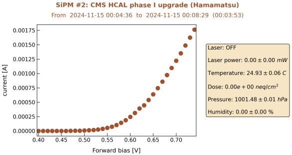


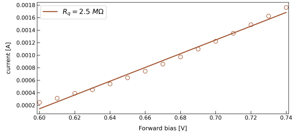
3. Noise I_{dark} for single value of $V_{bias} \Rightarrow$ point
4. Noise I_{dark} for range $V_{bias} \Rightarrow$ curve



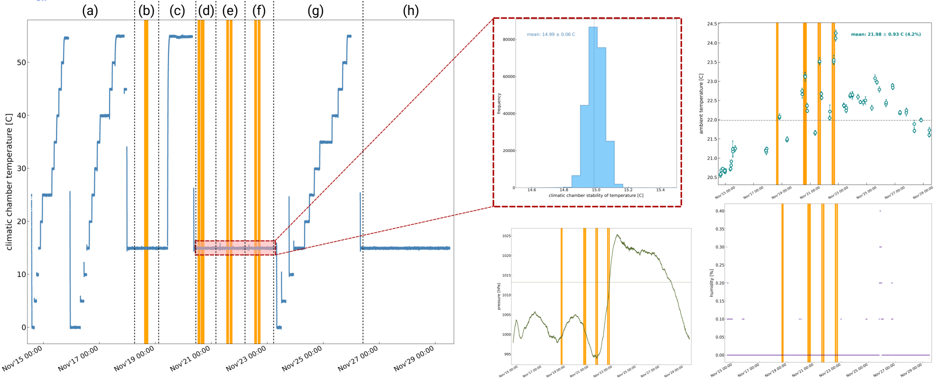


5. Quench resistance R_q for cell of SiPM on forward voltage $\Leftrightarrow$ linear fit $I_f(V_{bias})$
   $\partial V_{bias} / \partial I_f \simeq R_q / N_{cell}$ (N_{cell} – number of cells)





Prototype of stand to investigate aging of SiPMs: experiment & results

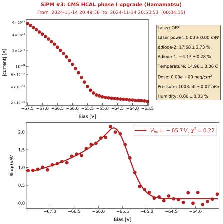


	Tag (date)	Temperature [°C]	Integral of dose [neq/cm^2]
(a)	**Initial point** (14 – 17/11/24)	0 ÷ 55 (step 5°C)	–
(b)	**First day** (18/11/24)	15	4.86×10^8
(c)	**Annealing in stand** (19/11/24)	55	4.86×10^8 (0)
(d)	**Third day** (20/11/24)	15	5.75×10^8 (0.89×10^8)
(e)	**Fourth day** (21/11/24)	15	6.63×10^8 (1.77×10^8)
(f)	**Fifth day** (22/11/24)	15	7.40×10^8 (2.54×10^8)
(g)	**Point before** (23 – 25/11/24)	0 ÷ 55 (step 5°C)	–
(h)	**Restore** (26 – 29/11/24)	15	–
	Annealing in oven (06 – 12/12/24)	240	–
	Point after annealing (13 – 15/12/24)	0 ÷ 55 (step 5°C)	–

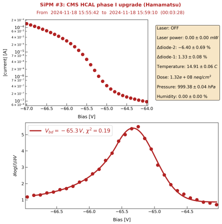
Prototype of stand to investigate aging of SiPMs: experiment & results

Breakdown voltage

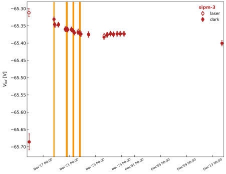
Initial point: I_{dark}



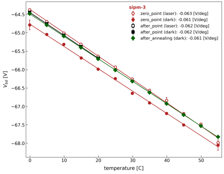
First day: I_{dark}, 1.3×10^8 neq/cm^2



V_{bd} vs dose ($T = 15°C$)

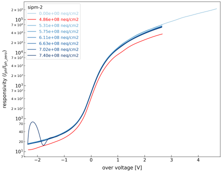


V_{bd} vs temperature

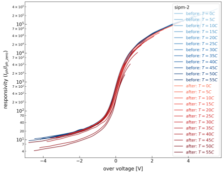


Linearity (photosensitivity)

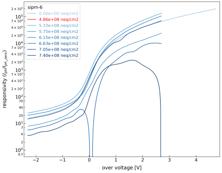
SiPM #2: dose dependence ($T = 15°C$)



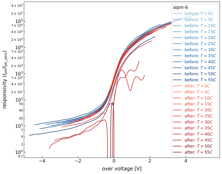
SiPM #2: temperature dependence (before & after)



SiPM #6: dose dependence ($T = 15°C$)



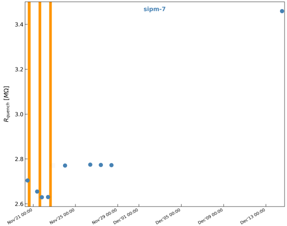
SiPM #6: temperature dependence (before & after)



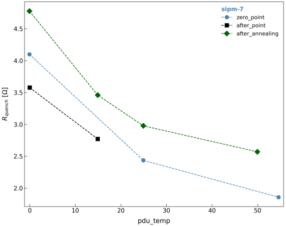
Prototype of stand to investigate aging of SiPMs: experiment & results

Quench resistance

SiPM #7: dose dependence ($T = 15°C$)



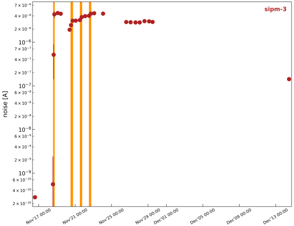
SiPM #7: temperature dependence



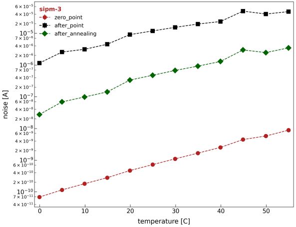
- Strong temperature dependence $R_q(0)/R_q(55) \simeq 2$ (initial point)
- After irradiation: $R_{bef}/R_{irr} \simeq -4\%$
- After restore: $R_{bef}/R_{rel} \simeq 4\%$
- After annealing in oven: $R_{bef}/R_{ann} \simeq 25\%$

Noise (point)

SiPM #3: dose dependence ($T = 15°C$)



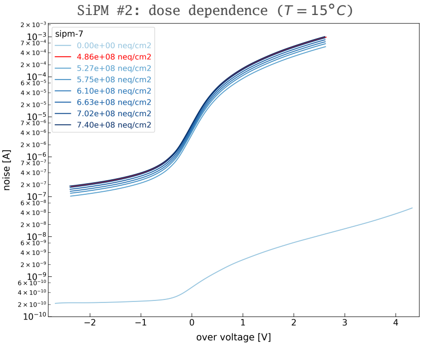
SiPM #3: temperature dependence

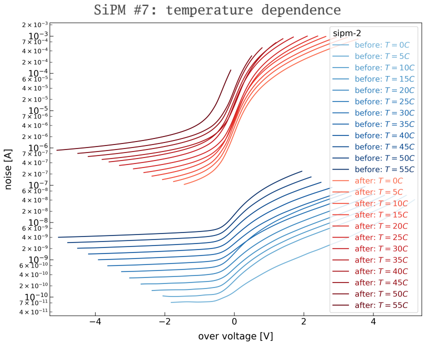


- First day: noises rapid increase by 4 orders $3 \times 10^{-10} \Rightarrow 4 \times 10^{-6}$
- Annealing in stand: noise reduction by 4 times $4 \times 10^{-6} \Rightarrow 1 \times 10^{-6}$
- Other 3 days: smooth increase to 4×10^{-6}
- Self restore: 2-fold decrease $4 \times 10^{-6} \Rightarrow 2 \times 10^{-6}$
- Annealing in oven: 20 times noise reduction $2 \times 10^{-6} \Rightarrow 1 \times 10^{-7}$

Prototype of stand to investigate aging of SiPMs: experiment & results

Noise (curve)





Achieved main results

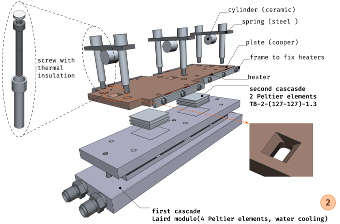
- Main goal of conducted experiment was test performance prototype of stand under flux of fast neutrons
- Tested SiPMs (which were designed to HCAL of CMS) are not used in real experiments. Obtained results are mainly important to check performance of stand
- The overall performance of stand prototype is good. The electronics of climatic chamber are able to operate under a flux of fast neutrons and DAQ is quite sufficient

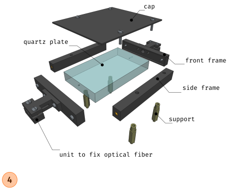
Systems of stand which should be redesined

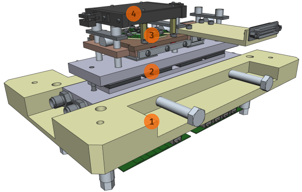
- Light distribution system needs to be upgraded in order to ensure uniform intensity and stability when stand is moved from BNCT to laboratory
- The temperature range of the climatic chamber needs to be increased, especially in the negative direction
- Initial dose should be decreased to 10^{-6} neq/cmq

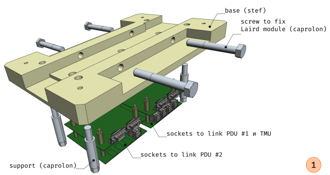
Stand to investigate aging of SiPMs

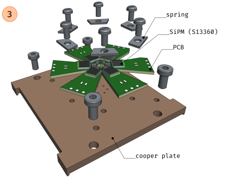
Mechanical design of climatic chamber and light distribution system

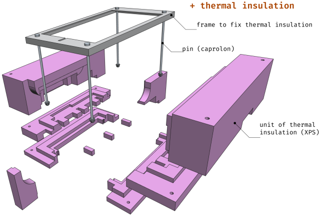






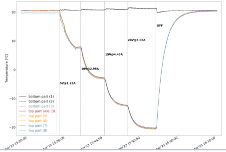




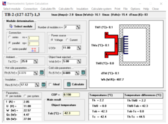


Calculation and testing of climatic chamber

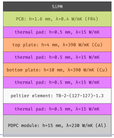
Test of Laird module



Performance of TB-2-(127-127)-1.3



Scheme of thermal resistance



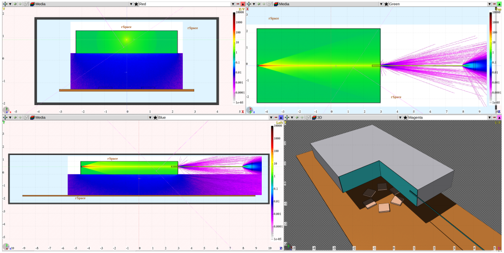
Obtained results (calculation)

- temperature range from $-40\ ^{\circ}C$ to $+70\ ^{\circ}C$ with good reserve
- it is need to 20 minutes to set $-40\ ^{\circ}C$ from room temperature level

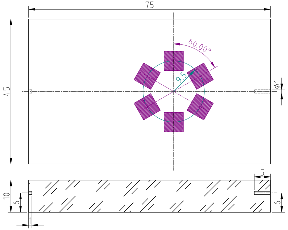
Stand to investigate aging of SiPMs

Simulation to evaluate the uniformity of light output from quartz plate

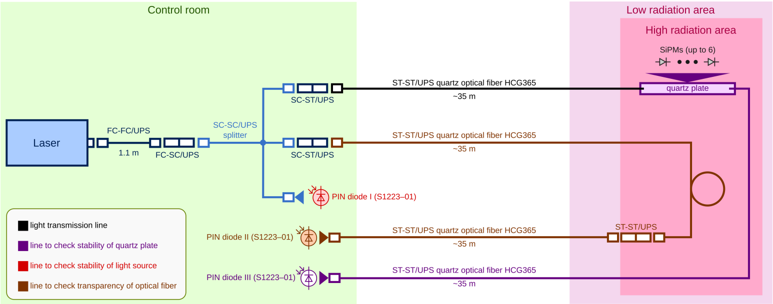
Example description of the geometry and light distribution



The final shape of the quartz plate. The nonuniformity of light flux across all SiPMs is 3%



Principal scheme of light distribution system

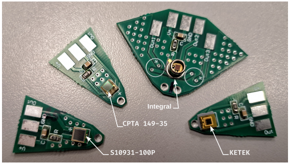


Stand to investigate aging of SiPMs

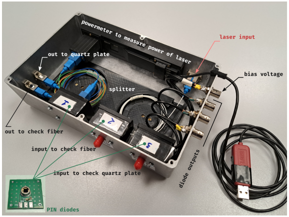
SiPMs to test of radiation damage

	S [mm^2]	cells
CPTA 149−35	4.41	1764
S10931−100P	9.0	900
S13360−6025PE	36.0	57600
S13360−6050PE	36.0	14400
Integral 35μm	1.44	1156
Integral 50μm	1.44	576
KETEK	xx	xx

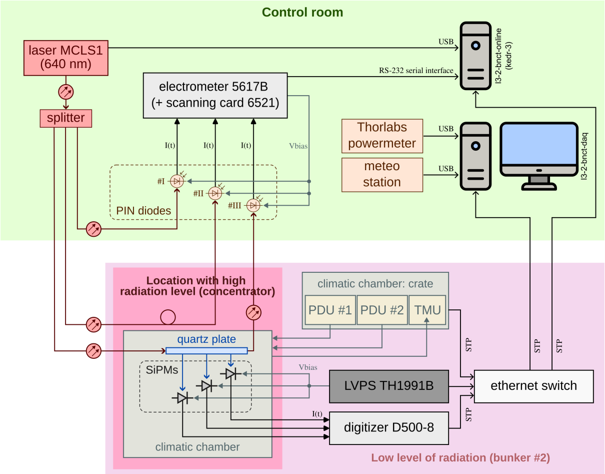
Manufactured PCBs with SiPMs



View of light box



Layout of stand



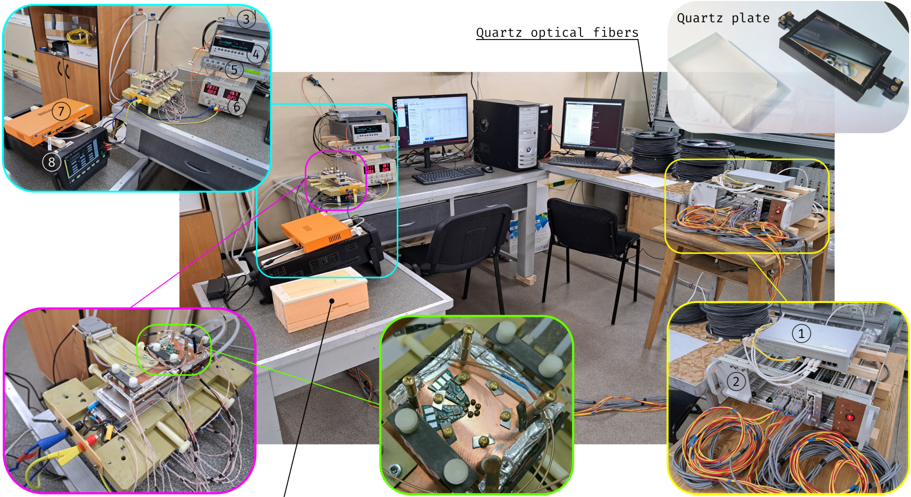
List of planned experiments (first stack of tasks)

- We will start with SiPMs by Integral production (these SiPMs will be used to upgrade ToF system of KMD-3 detector)
- In parallel scintillation strip will be tested to estimate the efficiency of neutrons registration (needs to Belle II muon system)

Stand to investigate aging of SiPMs: status

3. Light box
4. Electrometer
5. Laser

6. LVPS for Laird module
7. Digitizer
5. LVPS for SiPMs



Climatic chamber without insulation

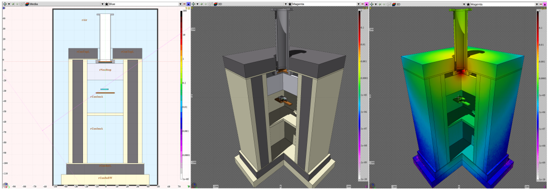
PCB with SiPMs

1. Ethernet switch
2. Climatic chamber electronics

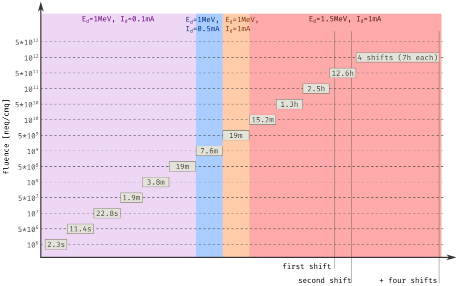
Stand to investigate aging of SiPMs: immediate plans

- Testing run in November 2024 demonstrated us that reduce initial value of dose (intensity of deutron beam) needs, in contrast to investigate degradation transparency of fibers (CMS)
- So, needs to start with a fluence of $10^6 \div 10^7$ *neq/cmq*. Subsequently, as dose integral increases, the neutron flux density can be increased depending on the behavior of tested SiPMs
  - We can play with energy and current of the deuteron beam, with location of SiPMs, and we can add some material (neutrostop)
  - Another option is to use a set of cooling diaphragms to collimate the deuteron beam. Design is done, manufacture is in progress

Simulation was performed to select optimal scenario



Designed scenario to carry out the experiment



Summary timetable in 2025

Summer: design and simulation have been conducted

September–October: all parts are manufactured and needed items are purchased

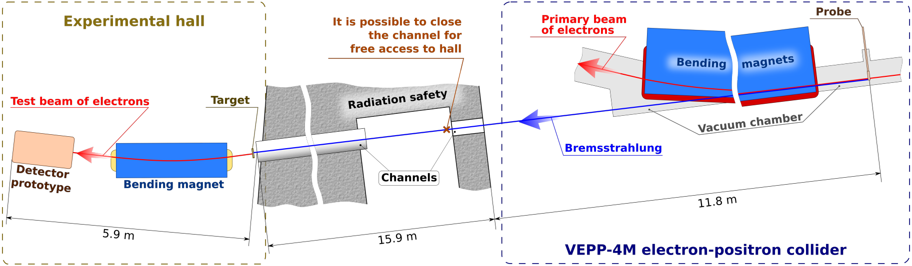
✓ **November:** installation and standalone verification systems of stand

First half of December: preparation of stand to experiment (calibration, carry out of testing runs and so on)

Second half of December: stand will moved to BNCT and the study of SiPMs aging will begin

3. Test Beam facilities

Layout of the test electron beam



Parameters of the beam	
Energy range	0.1 ÷ 3.5 GeV
Average intensity	50 ÷ 100 electrons/sec
Energy spread of the selected electrons	7.8% @ 0.1 GeV and 2.9% @ 3.0 GeV

- System to measure Bremsstrahlung intensity
- Trigger system on the base scintillation counters or two MCP PMT (in latest case time resolution is about 20 psec)
- Coordinate system, it is using GEM trackers ($\sigma_{x,y} \simeq 35 \div 50 \mu m$) and these trackers usually are installed between magnet and detector prototype
- Calorimeter which are located in the end of beam line ($\sigma_E/E = 1.3\%$ @ 3.0 GeV)

The facility is being used for

- Testing FARICH (Focusing Aerogel RICH) prototypes ⟺ for particle identification
- Calibration of coordinate detectors based on GEMs
- Measurement of the time resolution and detection efficiency of charged particle detectors based on microchannel plates
- Testing shashlik electromagnetic calorimeter of the MPD detector for NICA
- And so on

List of possible Test Beam facilities at BINP

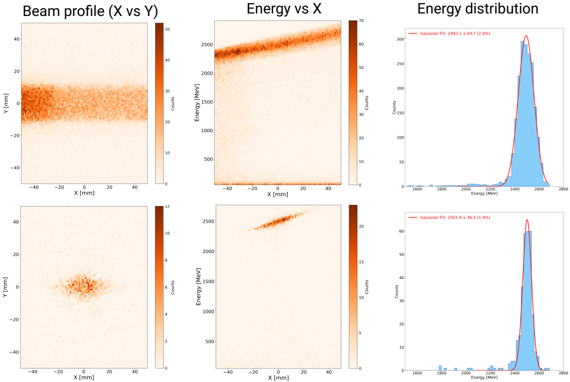
Accelerator/collider	Energy [MeV]	Current [mA]	Parameters of beam		
			energy [MeV]	intencity [Hz]	energy spread [%]
VEPP−4M (in operate)	4750	$10 \div 15$	up to 3500	100	2.9
VEPP−4C	1850	up to 15	1800	$\simeq 75$	$\simeq 4$
VEPP−6	2100	1500	2100	$\geq 1000^*$	$\leq 1^*$
Siberian circular photon source (SKIF)	3000	400	3000	$\simeq 400^*$	$\leq 1^*$

* with collimator

Very preliminary results of simulation for SKIF: test beam energy 2500 MeV, current of primary electron beam 400 mA

Without collimator:
- intensity > 1 kHz
- energy spread 2.6%
- high background level at the prototype testing site

With collimator:
- intensity $\simeq$ 400 Hz
- energy spread 1.4%
- low background level at the prototype testing site



4. Conclusion

- Existing BNCT facility in BINP provides neutron flux up to 10^{14} neq/cm^2. It has been demonstrated for the first time that at BINP it is possible to operate with such doses using of neutron beam
- In 2022 at BNCT investigation degradation transparency of optical fibers for CMS detector was conducted
- In 2024 stand prototype to investigate irradiation aging of SiPMs was manufactured and tested
- For now first version of stand has been designed and first experiment with SiPMs will be performed until 2025
- Test Beam facility at BINP in operate, simulation and design new possible Test Beam Facilities at BINP/SKIF are in progress. Existing Test Beam facility based on VEPP–4M collider is under optimization too (main goal reduce energy spread with preserve intensity)
- Finally, the Test Beam facility together with the stand for investigate of irradiation aging can provide a good situation for the development of new systems/detectors for HEP at BINP. In this scenario, it is possible to test a prototype using an electron beam, irradiate the prototype, and then test the prototype again using the beam

✓ **We are open to new cooperation and invite you to Siberia to work with beams of electrons, gammas and fast neutrons !**