Development of a physics program and detectors for experiments at CEPC

Leaders: Yu.I. Davydov

A.S. Zhemchugov

Deputy Leaders: A.B. Arbuzov

Yu.A. Kulchitsky

62nd meeting of the PAC for Particle Physics, 23 June 2025

Recommendation of the 60th PAC meeting

In 2024, we submitted to the PAC the project “Development of a particle registration technique in future experiments with the participation of JINR” within the frame of the theme 02-2-1151-1-2025/2025 of the JINR Topical Plan. The project was approved by the PAC with a recommendation:

Recommendation. The PAC supports the proposal for the opening of the new project, “Development of a particle registration technique in future experiments with the participation of JINR.” However, the PAC considers that the program presented is too general. The PAC encourages the team to prepare a more elaborate program outlining the specific goals and objectives of the project and to submit it to the PAC in one year. Consequently, the PAC recommends now opening the new project for one year with ranking A.

Report on the project activity

Over the past half year, we have made significant progress in fulfilling the tasks set in the project:

- An innovative method has been proposed for improving the basic characteristics of EM calorimeters of the shashlik type under limited efficiency of wavelength-shifting fibers. Monte Carlo simulations have shown that the use of this method can significantly improve the linearity of the response and energy resolution of the electromagnetic calorimeter.
- The effect of a ^{60}Co gamma irradiation on the scintillation properties of the inorganic scintillator BaF_2, pure and doped with yttrium, was studied. It has been shown that after irradiation, the fast component of BaF_2 emission degrades faster than the slow one.
- The influence of ^{60}Co gamma radiation on the properties of GaN transistors and amplifiers for silicon photomultipliers based on them was investigated. It is shown that the GaN transistors could be proposed for use as a radiation-resistant material for the amplifiers.
- Micromegas detectors were produced with DLC coating and tested for resistance to breakdowns. The stability of these detectors to multiple breakdowns and the possibility of their use under high rate of ionizing particles are demonstrated.
- Modeling of heterogeneous thick neutron detectors was carried out and the ultimate capabilities of these materials were determined.
- The light output of a triangular strip for a muon detector was investigated depending on the location of the particle passage. It is shown that triangular strips can be used in a muon detector.

More detailed information is available in the back up slides

Prolongation of the project

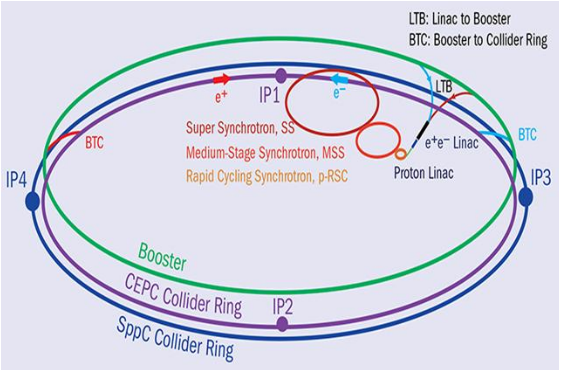
Following the recommendation of the 60th meeting of the PAC for Particle Physics, we propose to extend project for the next 2 years, for 2026-2027, with new name "Development of a physics program and detectors for experiments at CEPC"

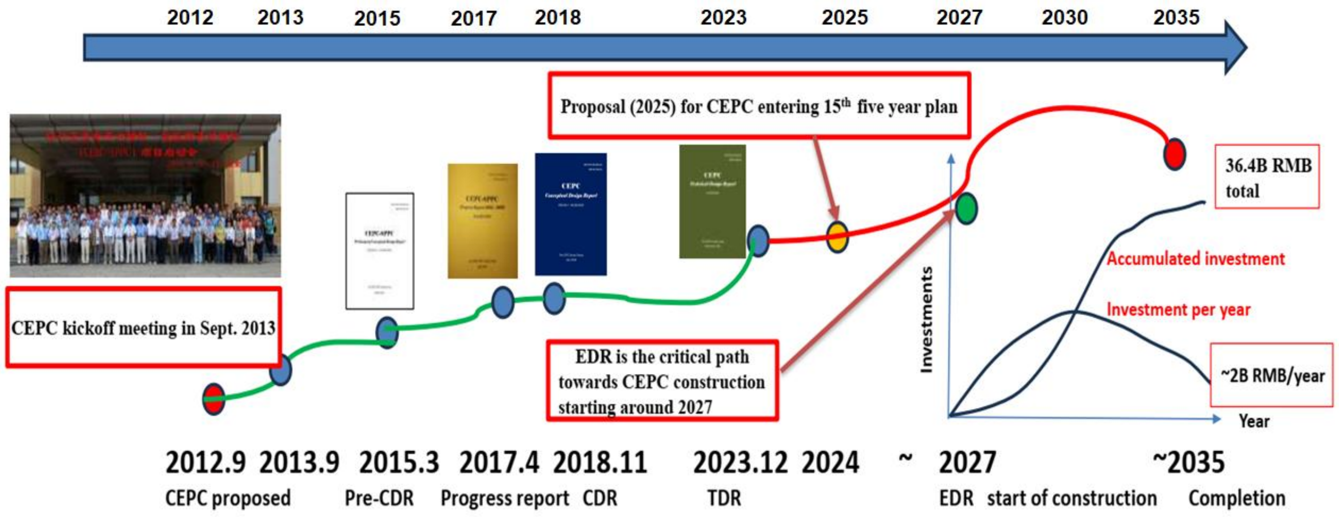
What is CEPC:

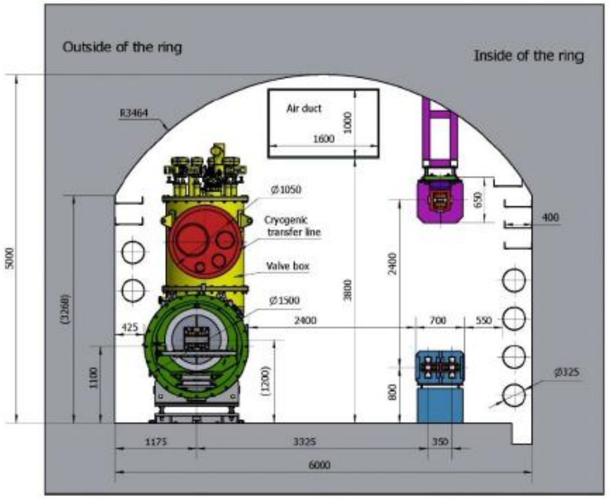
- Circular Electron-Positron Collider (CEPC) is an e^+e^- Higgs factory producing Higgs/W/Z bosons and top quarks, aims at discovering new physics beyond the Standard Model
- Proposed in China in 2012, after the discovery of the Higgs boson at the LHC. Construction is planned to begin around 2027 and begin operations in the mid-2030s.
- Probing new physics to 10 TeV (direct-indirect)
- Unprecedented precision on EW and QCD, rich flavor physics
- Upgrade: Super pp Collider (SppC) of $\sqrt{s} \sim 125$ TeV in the future

CEPC layout

- **Circular collider:** Higher luminosity than a linear collider
- **100km circumference:** Optimal total cost
- **Shared tunnel:** Compatible design for CEPC and SppC
- **Switchable operation:** **Higgs, W/Z, top**
- **Accelerator complex:** Linac, a 100 km booster and a collider ring





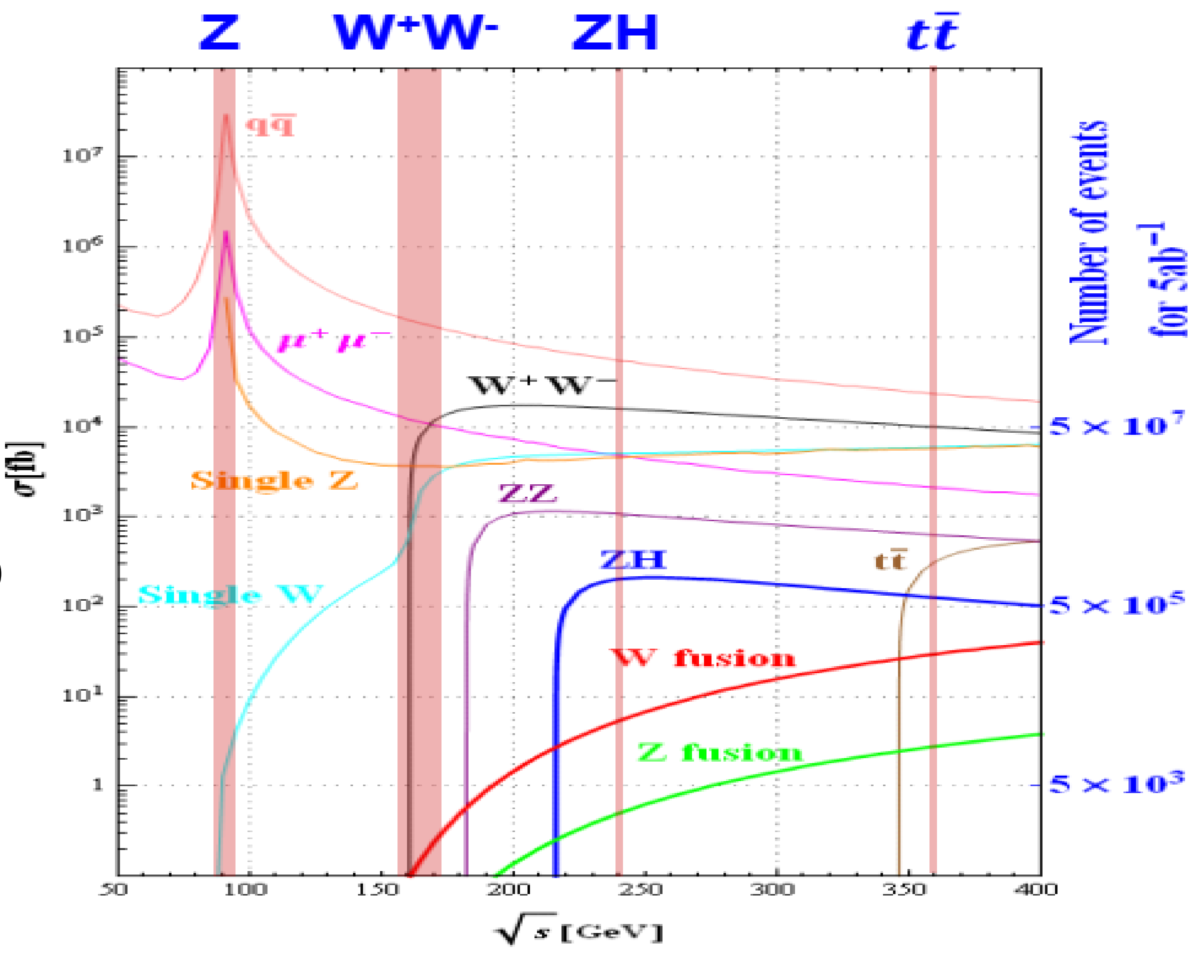


Common tunnel for booster/collider & SppC

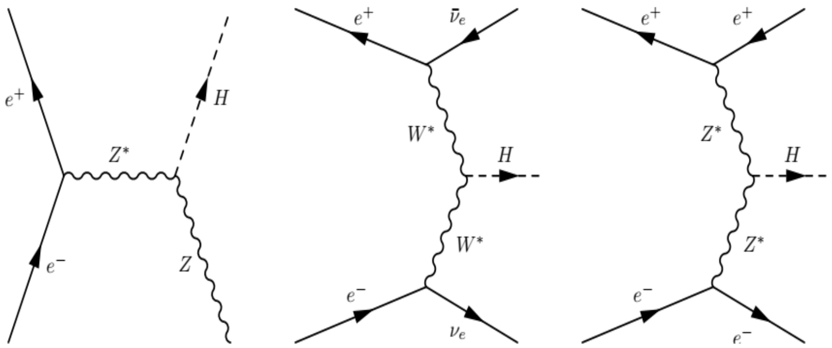
CEPC has strong advantages among mature electron-positron Higgs factories (design report delivered),
•**Earlier data**: collision expected in ~2035 (vs. FCC-ee ~ 2050), **larger tunnel cross section** （ee, pp coexistence)
•**Higher precision** vs linear colliders with more Higgs & Z; potential for **proton collider upgrade**.

Physics goals of CEPC

- **Precision study of Higgs: 91** (Z), **160** (WW), **240** (ZH), **360** (tt) GeV
- **Higgs Factory (>10^6 Higgs bosons)**:
  - **Higgs** (m_H, main quantum numbers JPC, couplings)
  - **Complementary** to **Linear** colliders
  - Looking for hints of **BSM physics:**
    - **Dark Matter**
    - **ElectroWeak phase transition** (EWPT)
    - **Long-Lived Particles (LLP),** …
- **Z & W factory** (>10^{12} Z_0):
  - **Precision test of SM**
  - **Rare decays,** …
- **Flavor factory: b, c, t and QCD studies**



Higgs boson study

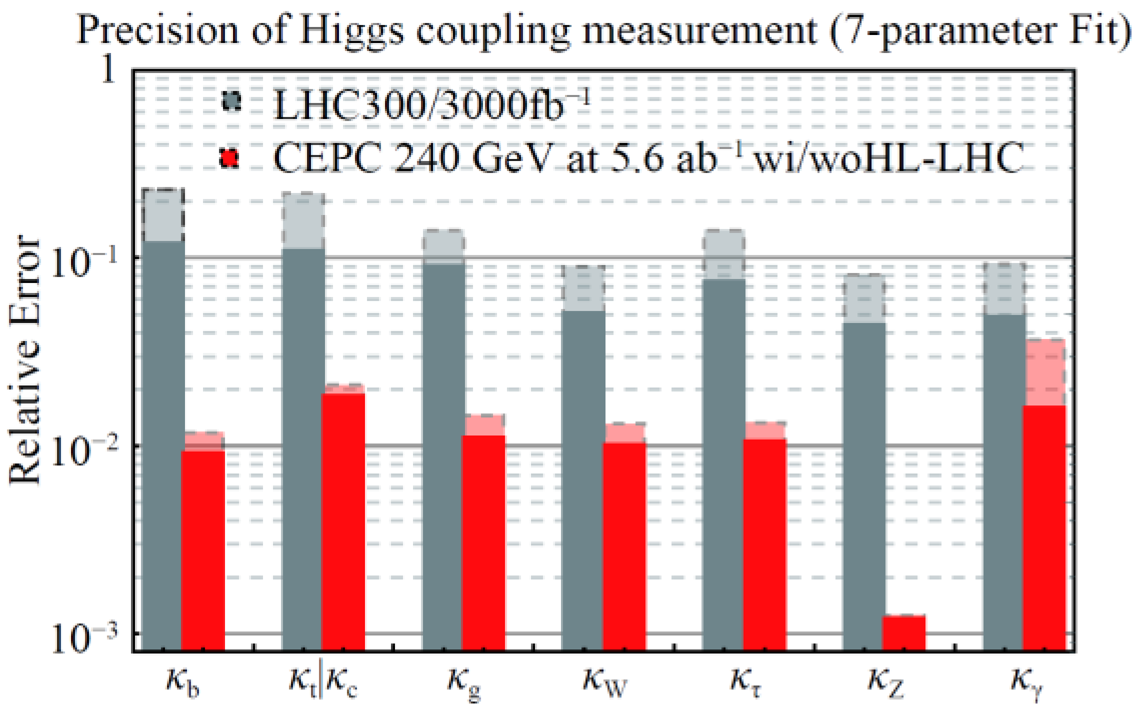


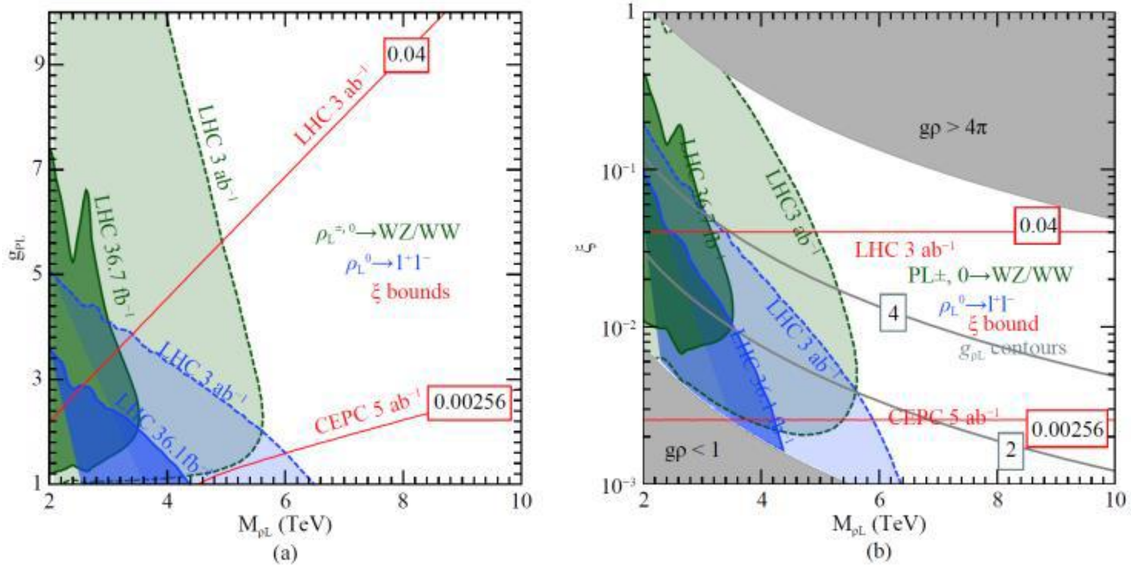
Higgs boson production processes:
$e^+e^-\rightarrow ZH$ (ZH associate production)
$e^+e^-\rightarrow \nu\bar{\nu}H$ (WW fusion),
$e^+e^-\rightarrow e^+e^-H$ (ZZ fusion)

- The Higgs boson physics is the main task of the experiments at CEPC for the first 10 years
- Higgs boson production at the energy $\sqrt{s}\sim 240\text{–}250$ GeV: $e^+e^- \rightarrow ZH$, $e^+e^- \rightarrow \nu\bar{\nu}H$, and $e^+e^- \rightarrow e^+e^-H$
- Higgs boson candidates can be identified using a mass recoil method, without labeling their decays
- The branching ratios of the Higgs boson decay can be determined by studying its individual decay modes
- Higgs boson decays, identified by their unique signatures, will be studied in the following modes:
  $H \rightarrow b\bar{b}/c\bar{c}/gg$, $H \rightarrow WW^*$, $H \rightarrow WZ^*$, $H \rightarrow W\gamma$, $H \rightarrow \tau^+\tau^-$, $H \rightarrow \mu^+\mu^-$, $H \rightarrow inv$
- A systematic study of the $e^+e^-\rightarrow ZX$ processes will be carried out to determine properties of the Higgs bosons with the best accuracy and new physics BSM searches using Monte Carlo generations for full detector simulations of signal and background events

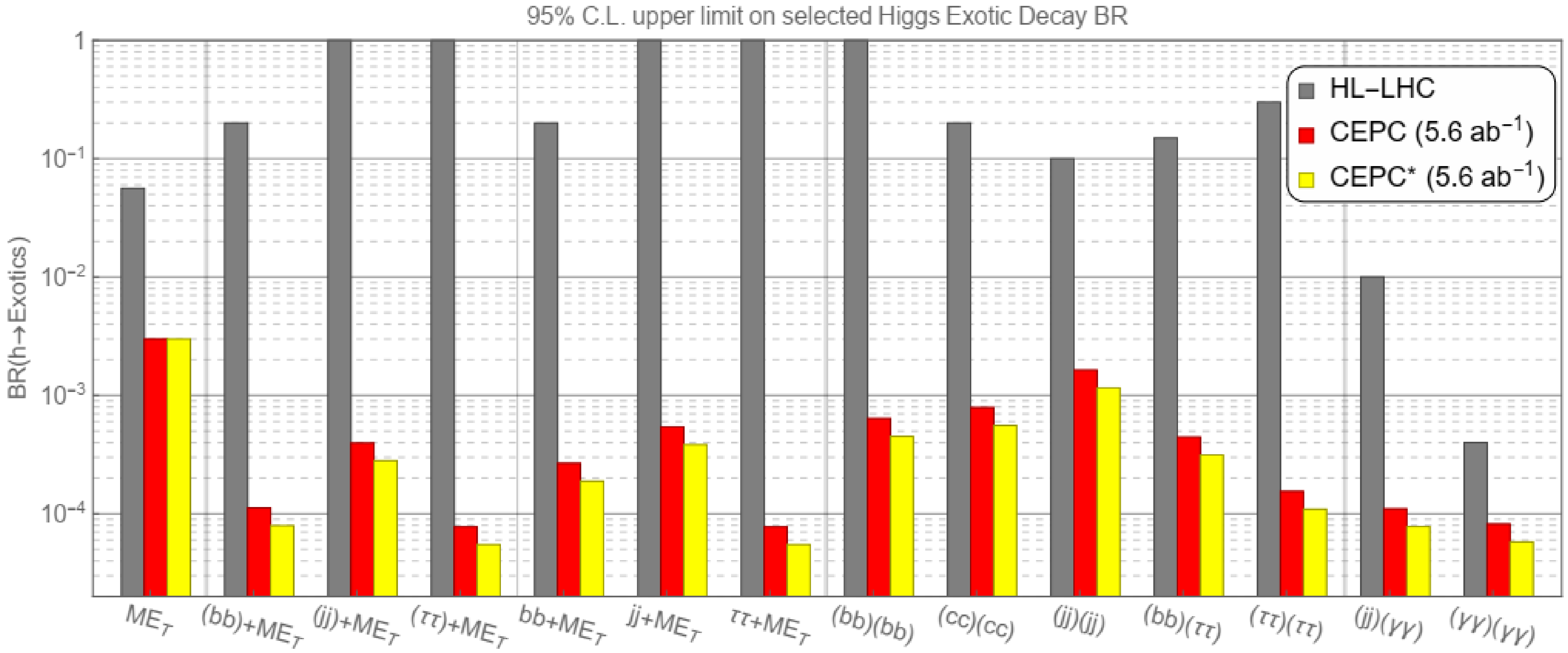
Physics at CEPC

- Higgs coupling measurement can be improved by orders magnitude
- Direct and indirect probe to new physics up to 10 TeV, an order of magnitude higher than HL-LHC
- Electroweak measurement can be improved by a large factor





Branching of selected Higgs boson exotic decays



- The 95% CL upper limit on selected Higgs exotic decay branching fractions at **HL-LHC and CEPC**.
- **The red bars correspond to the results using only leptonic decays of the spectator Z-boson.**
- **The yellow bars** further include extrapolation with **the inclusion of the hadronic decays** of the spectator Z-boson

CEPC operation plan and goals

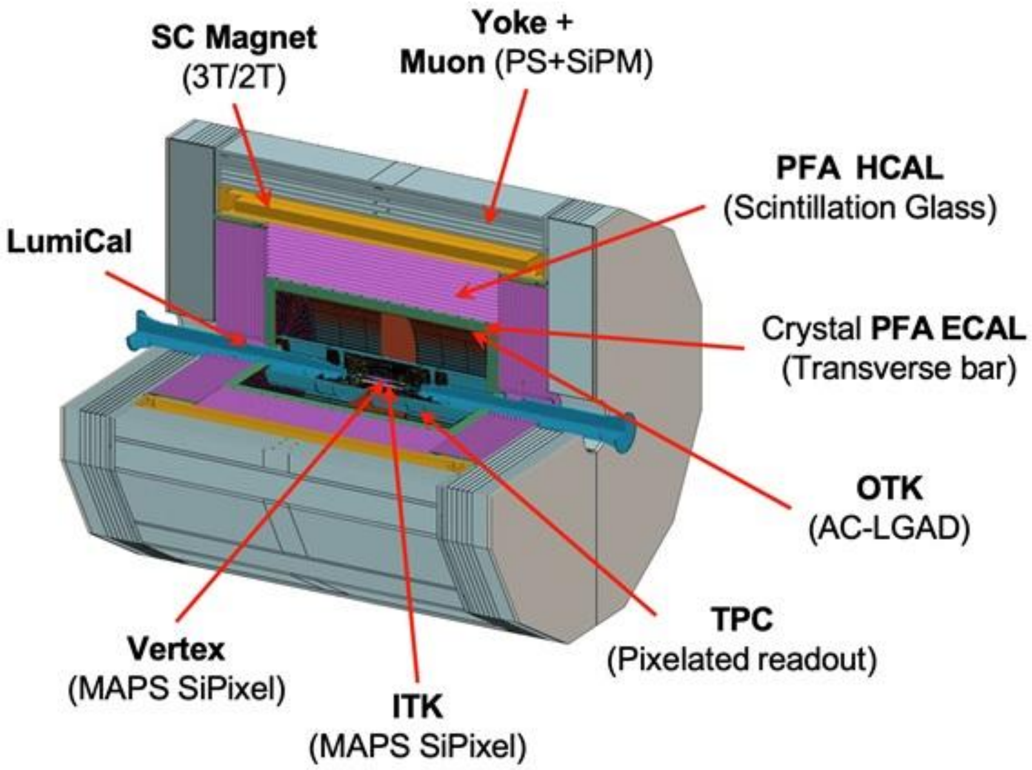
Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. per IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. per year (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	1	50	26.7	6.9	6.9	2.1×10^8
			30	16	4.2	4.2	1.3×10^8
$t\bar{t}$	360	5	50	0.8	0.2	1.0	0.6×10^6
			30	0.5	0.13	0.65	0.4×10^6

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.

** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.

*** Calculated using 3,600 hours per year for data collection.

Reference detector concept



- **Ultra-low-mass vertex detector:** four inner layers utilize 65 nm large-area single-layer **stitched sensors**, with the innermost detector radius reaching **11 mm,** + a double-layer ladder structure.
- **ITK:** based on **monolithic HV-CMOS pixel sensors**, 3 barrel layers and 4 disk layers at each endcap, **~20m²**.
- **TPC: pixelated** readout, **500×500μm²**
- **OTK:** one barrel layer and two endcap disk layers, based on **AC-LGAD** to measure **timing and position**
- **PFA-oriented calorimetry:** high-granularity homogeneous **crystal** ECAL and novel **glass scintillator** HCAL
- **Superconducting solenoid** → **3 T** magnetic field.
- **Muon** detectors in the return yoke.
- **LumiCal**: an AC-LGAD silicon wafer layer and a calorimeter utilizing LYSO crystals.

Expertise of the JINR group in the tasks arising in CEPC

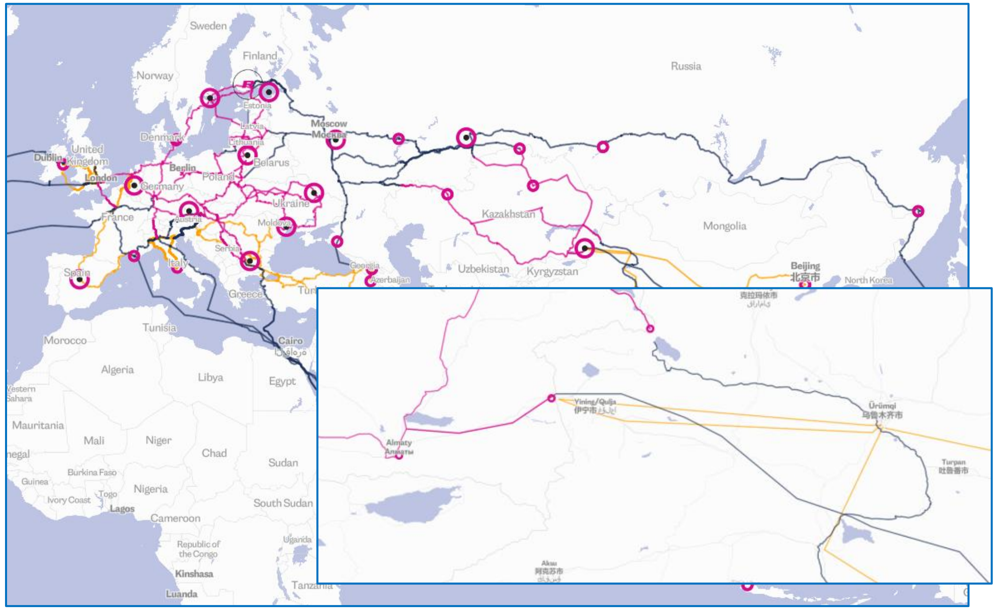
The group members have experience in solving most of the problems that arise in CEPC. The experience was gained through participation in leading experiments:

- Discovery of the Higgs boson and study of its parameters in the ATLAS and CMS experiments at the LHC
- Top quark mass measurement with record precision in CDF experiment at Fermilab
- Participation in physics analysis of DELFI experiment at LEP, BES III, etc.
- Development of Monte Carlo generators, calculation of radiation corrections for various HEP experiments
- Precise theoretical calculations in the EW physics for various experiments
- MLIT group members successfully support networks for the transmission of large flows of information and provide computer resources for storing and analyzing data for different experiments at JINR and abroad.
- Development of calibration methods and construction of electromagnetic and hadron calorimeters, gas detectors, scintillation systems for experiments MPD and SPD at NICA, ATLAS and CMS at LHC, CDF and Mu2e at Fermilab, etc.

CEPC Computing vs JINR–China IT collaboration

- JINR in Computing for the China HEP projects
  - ✓ Tier-1 Center for JUNO Distributed Computing (realization MoU since 2022)
  - ✓ BES-III and JUNO grid development (DIRAC, grid monitoring system, etc.)
- China-JINR Workshop on Software and Computing for Future HEP Experiment (15–19 Sept 2024, Baikal lake)
  - ✓ issues of cooperation between IHEP and JINR in the field of computing and software BESIII, JUNO experiments**, planned experiments at CEPC and NICA colliders**
  - ✓ R&D of new computational technologies in particle physics
- CEPC Computing (JINR Side) in 2026-2027
  - ✓ refining (fitting) the CEPC computing model
    - data model, data processing model
    - requested resources and sites are involved in
    - workload, job submission
  - ✓ JINR obligations in CEPC Computing (to be discussed and elaborated)
    - responsibility of JINR site, incl. pledges (CPU/disks/tapes)
    - site participation/part of CEPC distributed infrastructure (MoU?)
    - participation in development of interware and applied (physics) SW (reconstruction algorithms, collaboration tools, etc.)

Strategic long-term plan



- Organizing a high-speed links between JINR and China centers are being studied
  - ✓ negotiations with network operators in RF
  - ✓ commitment of JUNO/BESIII/NICA/Baikal-GVD/?
  - ✓ actual interest of China scientific centers

Vital matter of JINR teams in China projects

JINR contribution to the physics program and computing

- Providing theoretical support:
  - Development of physics program
  - Calculation of radiative corrections
  - Creation of advanced Monte Carlo tools
- Contributions to the Physics Program:
  - A systematic study of the $e^+e^- \to ZX$ processes to determine properties of the Higgs bosons with the best accuracy
  - The branching ratios of the Higgs boson decay will be determined by studying its exotic decay modes and new physics BSM searches
- Electroweak Physics:
  - precision EW at the Z peak and WW threshold
  - high energy EW: diboson, difermion
  - precision theoretical calculations
- Study of a flavor physics (heavy quarks, tau lepton)
- Computing for CEPC (JINR Side) in 2026-2027:
  - responsibility of JINR site, incl. pledges (CPU/disks/tapes)
  - site participation/part of CEPC distributed infrastructure (MoU?)
  - participation in development of interware and applied (physics) SW (reconstruction algorithms, collaboration tools, etc.)

JINR's contribution to the development of detectors

ECAL:

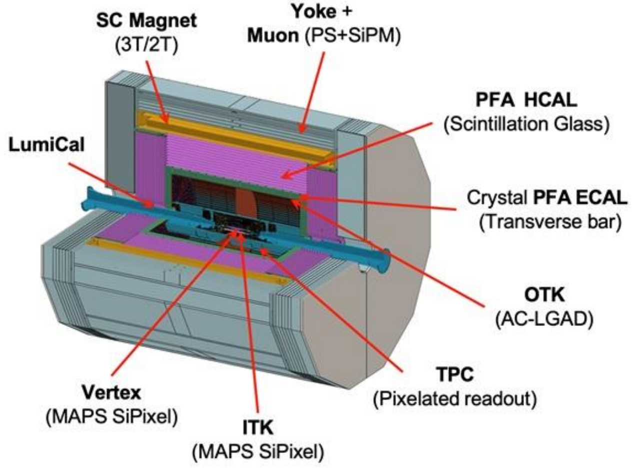
- Development of calibration methods for ECAL
- Participation on R&D on crystal units: joint efforts on crystal, SiPM
- Crystal-SiPM non-linearity effects: measurements and validation of MC model
- Participation in full-scale crystal calorimeter prototype creation and beam tests
- Irradiation studies on crystals and SiPM

GS-HCAL:

- Development of calibration methods for GS-HCAL jointly with ECAL and separately
- Participation in optimizing GS-SiPM coupling and performance
- Participation in creation of full-size GS-HCAL prototype and in beam tests

Muon:

- Study strips up to 5m long, increase the light yield and light collection
- Participation in multiple modules creation for system testing
- Carry out the long-term stability and radiation hardness testing
- Simulation of track reconstruction and low momentum measurement



TPC:

- Development of Micromegas prototypes at JINR for pixelated TPC
- Participation in development of the full drift length prototype
- Gas parameters study: Drift velocity, Attachment coefficient, T/L Diffusıon, etc.

Project personnel

DLNP (42): Yu.Davydov, A.Zhemchugov, Yu.Kulchitsky, A.Guskov, A.Artikov, L.Kalinovskaya, G.Lykasov, L.Gladilin, A.Gongadze, I.Eletskikh, I.Boyko, D.Chokheli, I.Suslov, N.Huseynov, V.Lyubushkin, A.Simonenko, Y.Dydyshka, V.Yermolchyk, A.Sapronov, R.Sadykov, L.Rumyantsev, A.Prokhorov, R.Lee, N.Atanov, I.Zimin, O.Dolovova, V.Baranov, I.Vasilyev, V.Malyshev, E.Plotnikova, P.Tsiareshka, D.Dedovichv, T.Lyubushkina, A.Boikov, V.Kiseeva, V.Moskalenko, A.Tropina, A.Kampf, A.Shalyugin, O.Atanova, V.Rogozin, A.Dadashova

BLTP (6): A.Arbuzov, S.Bondarenko, V.Zykunov, M.Savina, V. Bytev, U.Voznaya

VBLHEP (11): V. Karzhavin, V. Chmill, F.Ahmadov, A.Lanyov, V.Shalaev, V.Perelygin, I.Zhizhin, Yu.Ershov, A.Golunov, D.Budkovsky, D.Kozlov

MLIT (9): S.Shmatov, A.Nikitenko, O.Kodolova, N.Voytishin, D.Oleynik, A.Petrosyan, I.Pelevanyuk, Yu.Korsakov, K.Slizhevsky

№	Category employee	Core staff Amount of FTE
1.	scientific staff	25.4
2.	engineers	1.8
3.	professionals	0
4.	employees	0
5.	workers	0.4
	Total:	**27.6**

In total: 68 people with 27.6 FTE

Project resources

Names of costs, resources, sources of funding	Cost (thousands of dollars) resource requirements	Cost, distribution by year	
		1st year	2nd year
International cooperation (IC)	200	100	100
Materials	100	50	50
Equipment and third-party services (commissioning)	300	150	150
Resources required, normo-hours			
The amount of FTE	27.6	27.6	27.6
Accelerator/installation	200	100	100
Reactor	600	300	300
Budgetary resources (thousands of dollars)			
JINR budget	600	300	300

Summary

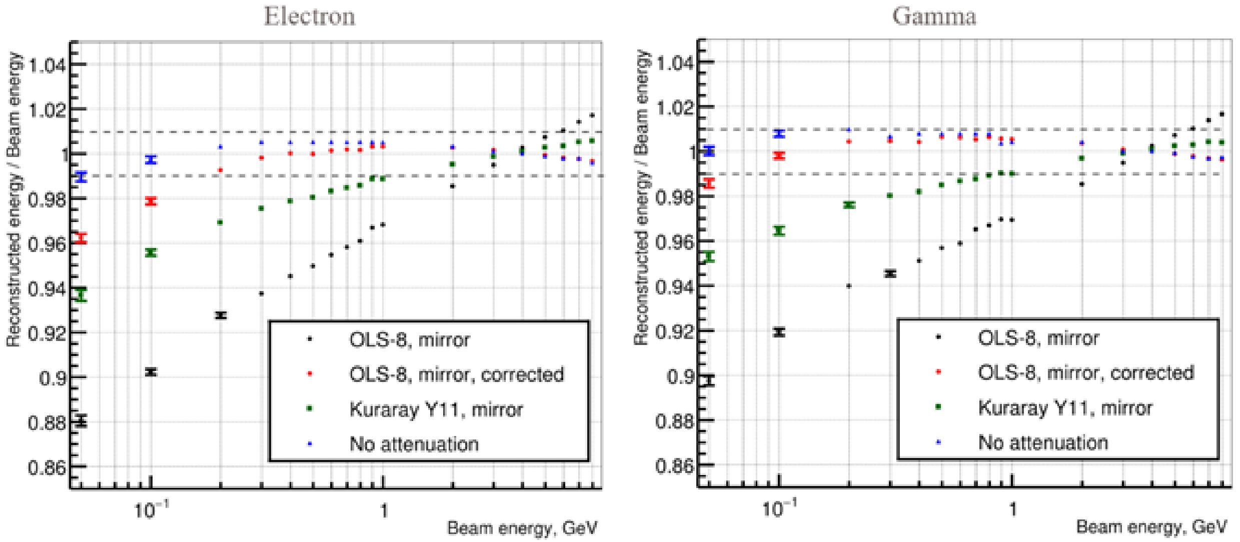
- The preparation of the CEPC project is progressing successfully and is approaching the stage of readiness of the detector TDR and the creation of international collaborations. A decision on whether to begin construction of the collider is expected in about a year.
- The project is proposed to be extended for two years, starting in 2026. The aim is to make proposals for the physics research program, to participate in software and computing development, to carry out a series of detector R&D aimed at further use in CEPC and to prepare for future research in this area.
- The JINR group is well balanced to solve all the tasks set in the project. The group members have extensive experience in collider physics research program development, data simulation and analysis, in computing and software development, in R&D and detector construction.
- Over the next two years, the cornerstone for JINR's future full participation in CEPC experiments will be laid, provided the construction of this accelerator is approved by the Chinese government.

Back up slides

Improving the linearity and energy resolution of the ECAL

- An innovative method has been proposed for improving the basic characteristics of EM calorimeters of the shashlik type under limited efficiency of wavelength-shifting fibers
- Monte Carlo study was carried out within the framework of the developed model of the basic characteristics of the electromagnetic calorimeter of the shashlik type
- Monte Carlo simulations have shown that the use of this method can significantly improve the linearity of the response and energy resolution of the electromagnetic calorimeter

- The Pb-scintillator calorimeter model uses fibers with a short attenuation length
- An innovative method has been proposed that uses an ordered arrangement of scintillation plates in order of decreasing light collection efficiency
- Figure shows a comparison of ideal fiber (no attenuation), Kuraray Y11 and OLS-8. The proposed method allows to improve basic characteristics of ECAL



Results were reported at the IX SPD CM (May 2025, Yerevan, Armenia)
Article prepared for submission to a journal

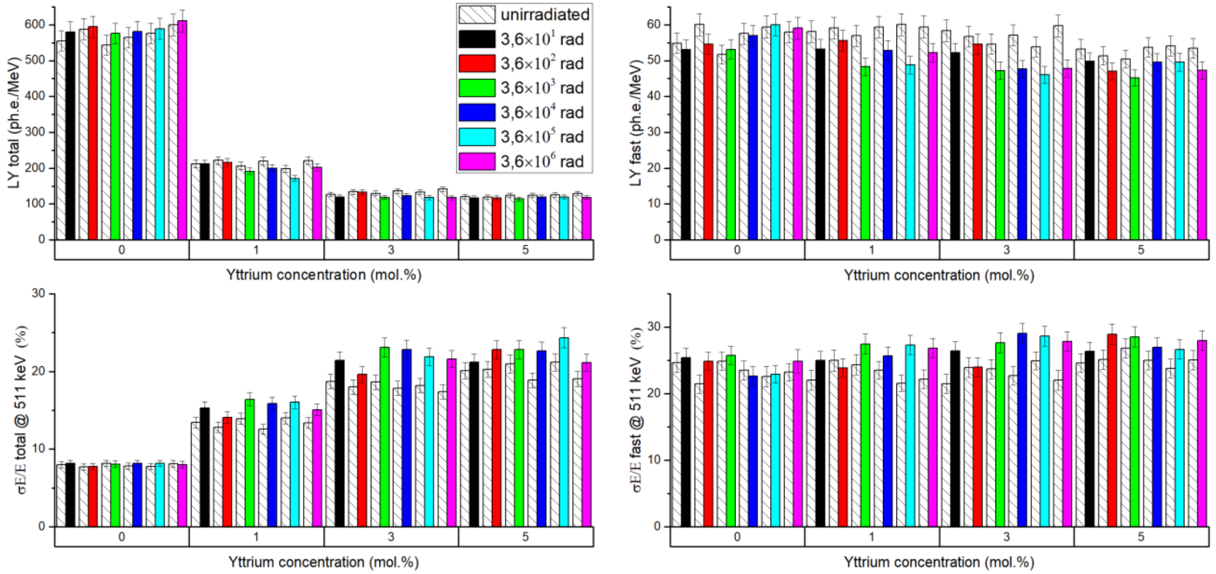
Study of radiation hardness of inorganic scintillators

Radiation hardness of pure and yttrium-doped BaF_2 crystals was studied. The crystals were irradiated at the gamma-irradiation complex of the Institute of Radiation Problems (Baku) with a radioactive source of ^{60}Co

- Crystals have dimensions 10x10x10 mm^3
- 6 groups of crystals, each of which consisted of pure BaF_2 and doped samples with yttrium at 1, 3 and 5 mole percent
- 6 group of crystals were irradiated to 36 rad, 360 rad, 3.6 krad, 36 krad, 360 krad, 3.6 Mrad, respectively.

    - Each crystal was measured before and after irradiation
    - A ^{22}Na gamma source was used to characterize the samples

- After irradiation, the light transmittance decreased in the region of 200-350 nm for all samples, the greatest decrease was demonstrated by samples with 3% yttrium
- Energy resolution deteriorated in all irradiated samples
- The light outputs of all samples decreased after irradiation, the greatest decrease is demonstrated by samples with 3% yttrium doping. These same samples have the greatest drop in the light yield of the fast component.

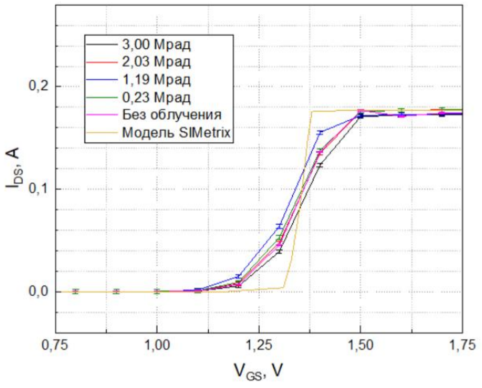


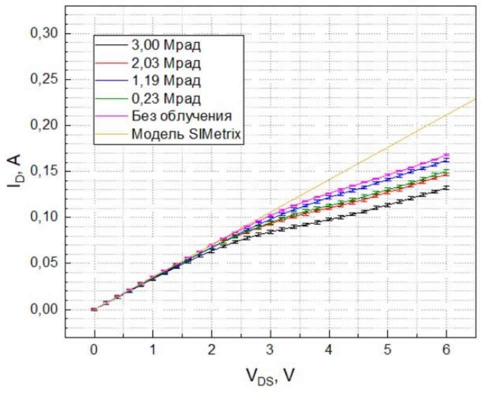
Preliminary results were presented at the session of the NPS of the DPS of the RAS (February 2025, Moscow)
The article is being prepared for publication.

Radiation hardness of GaN transistors

GaN transistors IGLR60R260D1 (Infineon, Germany) were irradiated with ^{60}Co gamma source.
Samples were irradiated to 0.23 Mrad, 1.2 Mrad, 2 Mrad and 3 Mrad

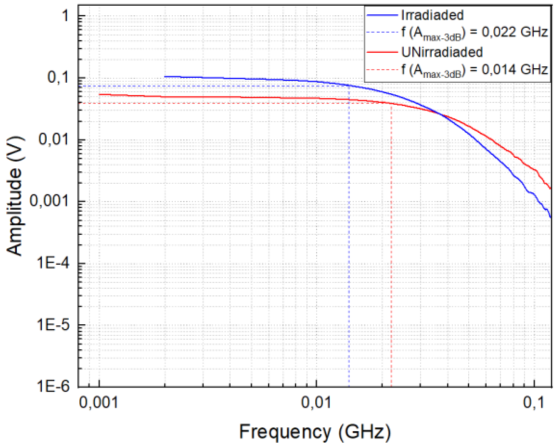
Characteristics of IGLR60R260D1 transistor

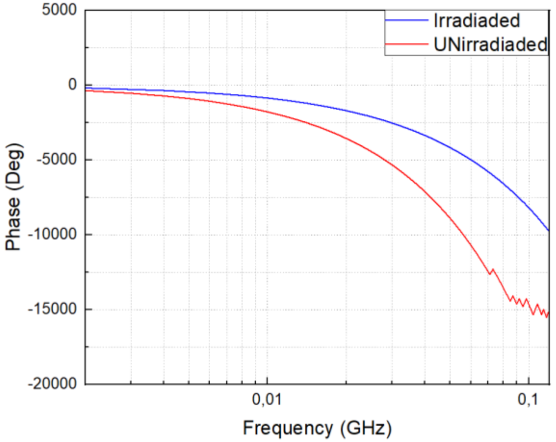


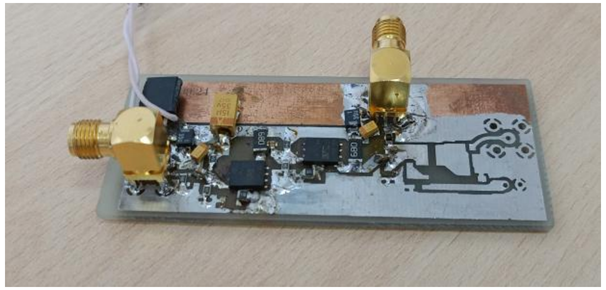


Input and output characteristics of the transistor. For the input characteristic V_{DS}=5 V, for the output characteristic V_{GS}=1.3 V

Comparison of Bode plots for amplifiers with irradiated and non-irradiated transistors



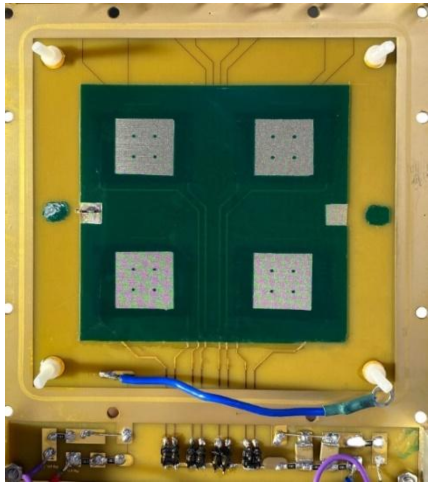




Amplifier with IGLR60R260D1 transistor

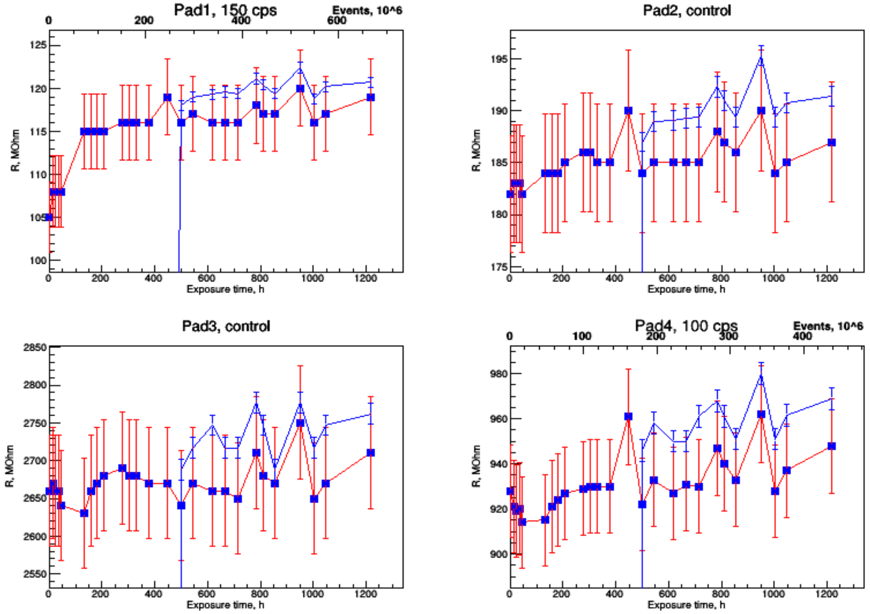
The study showed sufficient radiation hardness of the GaN transistors at an absorbed dose of up to ~3 Mrad. GaN is a promising radiation-resistant material for developing amplifiers for modern high-load detectors.

Development of microstructured gas detectors



- Micromegas detectors were produced with DLC coating and tested for resistance to breakdowns.
- An experiment was conducted to accumulate multiple breakdowns (about 100 million per cm^2) and study their influence on the characteristics of a detector with a resistive anode made of DLC coating.
- The stability of these detectors to multiple breakdowns and the possibility of their use under high rate of ionizing particles are demonstrated

- 50 μ thick flexible polyimide boards with reading electrodes were developed and manufactured for the production of a prototype of a detector using Bulk MicroMegas technology
- Prototype detector model using Bulk MicroMegas technology with a small amount of substance has been manufactured
- A method for insulating an anode high-voltage mesh electrode using photolithography has been developed for the manufacture of a well-type electron multiplier with a resistive anode (RWELL).

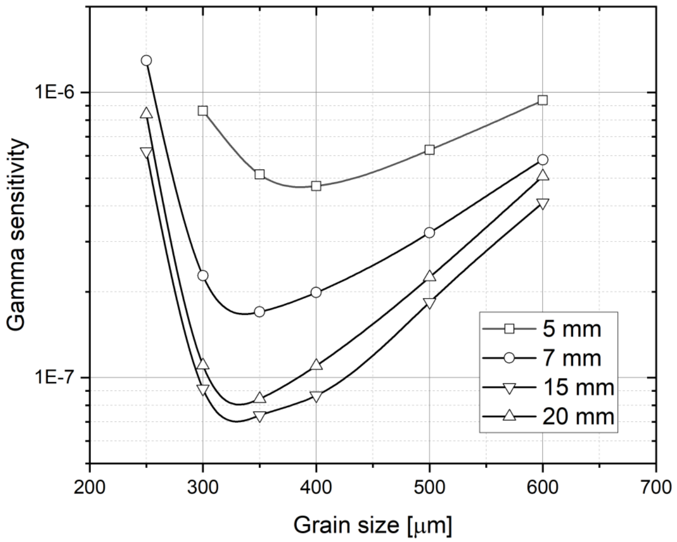


Change in DLC coating resistance with accumulation of multiple breakdowns

Progress in the development of heterogeneous neutron detectors

- Scintillation materials based on granular neutron scintillators manufactured in the Russia
  - Samples were made on the basis of LRB-1 and LRB-2 scintillators (manufactured by Luminophor, Stavropol).
  - LRB scintillators are made by fusing ZnS(Ag) and B_2O_3 crystals and then grinding them into powder with grain sizes of 0.7 mm.
  - LRB-type scintillators fixed with RT-601 and RT-604 silicone compound (Wacker, Germany)

- Simulation of heterogeneous thick neutron detectors
  - MC simulation showed that the thermal neutron conversion efficiency cannot exceed 0.82, which almost corresponds to a homogeneous layer of NE 912 with a thickness of 1 mm (0.79).
  - With a compromise value of 0.7 neutron conversion efficiency for a 15 mm thick composite, a gamma sensitivity of $S = 7\times10^{-8}$ can be obtained, an order of magnitude lower than that of NE 912 with a thickness of 1 mm.

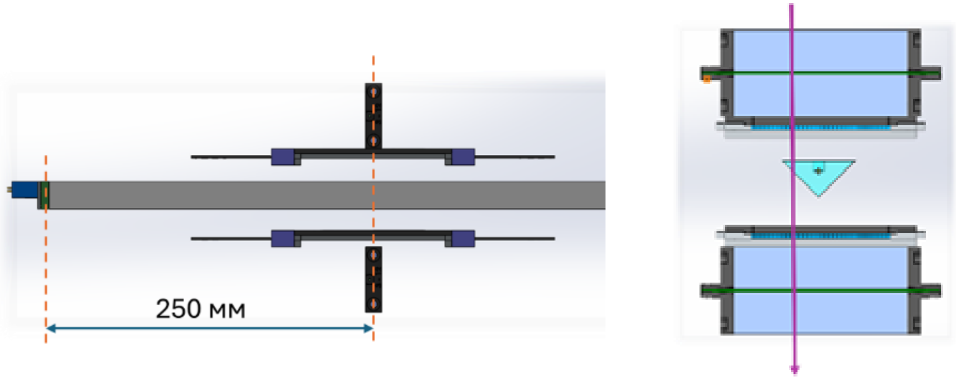


Gamma sensitivity versus grain size of NE 912 at a fixed neutron conversion efficiency of 0.7 for composite thicknesses of 5, 7, 15 and 20 mm.

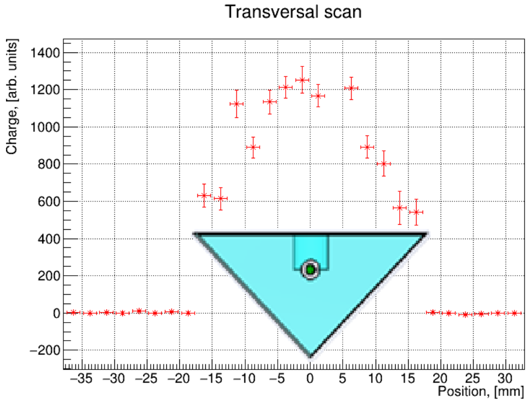
The article has been prepared for publication

Test of a triangular strip for muon detectors

Muon systems typically use long scintillation strips with signal readout using WLS fibers
The strips can have a rectangular or triangular cross-section with the fibers placed in grooves or holes inside the scintillators.



Side and end view of the installation



Light collection depending on the position across the strip

A transverse scan of a triangular cross-section strip on cosmic muons was performed:

- The cross-section of the strip is a right triangle with a base of 33 mm and a height of 17 mm
- The fiber is inserted into a longitudinal hole in the center of the strip
- Muons were selected by two 32-channel hodoscopes with 2x2 mm2 Kuraray SCSF-81J scintillation fibers
- The results demonstrate high light output across almost the entire strip cross-section
- Further plans for strip research include studying the light collection and attenuation length of rectangular strips with different fiber locations and diameters