Development of a particle registration technique in future experiments with the participation of JINR

New project proposal

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The Goals and Objectives of the Project

The goal of the project is the development of detector systems for accelerator experiments and new approaches to particle registration and identification.

The goals set in the project are aimed at solving problems arising in future collider experiments at NICA, at the Super c-tau factory (SCT) in Russia, at the Super tau-charm facility (STCF) and the Circular Electron Positron Collider (CEPC) in China, and at accelerators with fixed targets at intermediate and high energies, as well as in the search experiments Mu2e-II, and Comet (phase 2).

Microstructure and straw gas detectors	Development of electromagnetic calorimeter prototypes	Radiation resistance of materials and electronics	New scintillators for thermal neutrons	Optimizing the scintillation detector systems	MC simulation methods and application for prototypes of EMC and HC
Straw tubes	Longitudinal granulation simulation	BaF2, LYSO	Composite scint. with suppressed gamma sensitivity	Simulation of CRVs and comparison of prototypes with different strips	Modelling the response of an electromagnetic calorimeter
Well-type and Micromegas	Beam tests	Electronics components and preamps	Simulations and beam tests	Scint.+SiPM+front-end to get time res. ~50 ps	Analysing simulated data and realisation of efficient reconstruction methods

For more efficient use of human and financial resources, we propose to combine these activities within one project

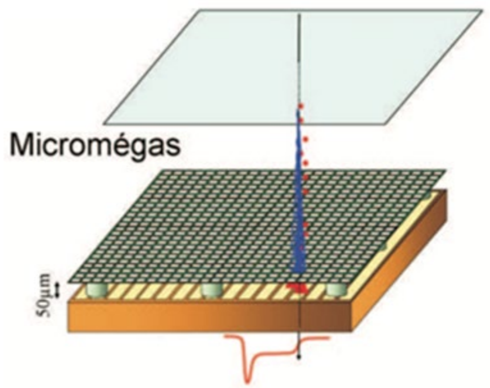
Our experience

Project participants have been fruitfully engaged in the development and research of new detectors, simulation and data analysis methods for a number of years within the framework of various projects and activities:

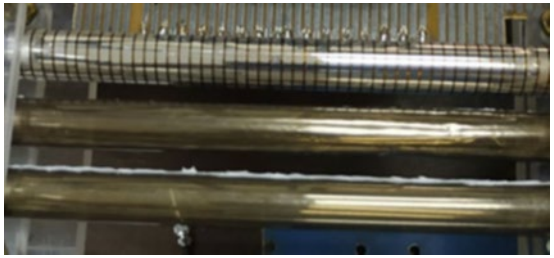
- Made important contributions to the construction and modernization of the CDF-II facility at FNAL, to data analysis and obtaining outstanding results, including precision measurement of the top quark mass
- Group members played a crucial role in the ATLAS Tile Calorimeter construction, maintenance and operation, upgrade. Significant contribution was made to the development of methods for analysis and MC simulation of the combined ATLAS calorimeter, its calibrations, study of its parameters, etc.
- Played a key role in the development of the calorimeter, CRV and preamplifiers, test measurements and preparation for mass production of the EM calorimeter and CRV system of the Mu2e experiment at FNAL
- Made a significant contribution to the modernization of the MEG-II detector and obtaining new record data in the search for the process $\mu \to e\gamma$
- Conducted important research on the radiation hardness of various detectors and materials
- Developed and studied various detectors, including microstructure and straw gas detectors, composite detectors for detecting thermal neutrons

Some details are in the backup slides

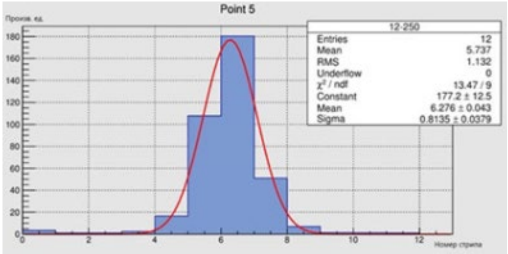
Development of microstructured and straw gas detectors



- We’ll continue our research work to create and test microstructured gas detectors with resistive elements and coatings based on diamond-like carbon (DLC).
- It is planned to develop a technology for the production of microstructured gas detectors designed to operate at high beam rate.
- Gas detectors with parameters (gas gain ~20000, energy resolution up to 20%, spatial resolution up to 200 μm) comparable with the best existing analogues will be developed and created, with the possibility of production on the basis of DLNP JINR.
- Technology for producing resistive cathode coatings based on DLC in a wide range of surface resistances (from 100 kΩ to GΩ per square) was developed by our colleagues from the IE NAS of Belarus (Minsk).

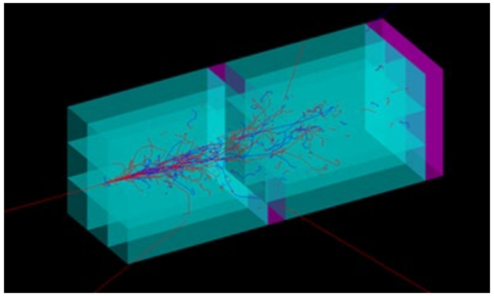


- Work will continue on the study of thin-walled straw detectors with resistive cathodes (based on DLC) with data reading from external strips.
- Technology will be developed, and prototypes of straw detectors with record-thin walls (less than 12 μm) will be created and studied in order to build detectors with a minimum amount of matter in the path of particles.



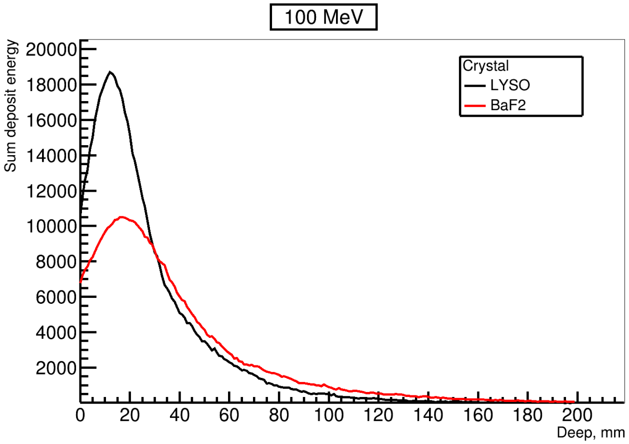
All tests of detector prototypes will be carried out on cosmic muons, on radioactive sources in our sertified lab, on accelerator beams at LINAC-200, and on test beams at VBLHEP

Development of prototypes of electromagnetic calorimeters



One of the trends in the development of calorimeters is the creation of detectors with a high degree of granularity in the transverse and longitudinal directions.

Crilin (Crystal Calorimeter with Longitudinal Information) longitudinal segmentation calorimeter is being developed for use in a future muon collider [*S.Ceravolo et al. JINST 17 P09033 (2022);C.Cantone et al. Front. Phys. 11:1223183 (2023)*]

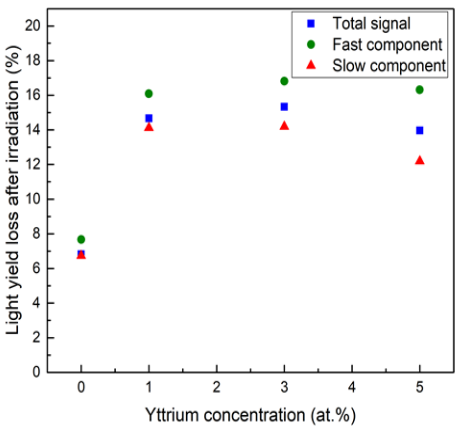


Energy losses along the length of the crystals. The crystals have dimensions of 30x30x200 mm^3. An electron beam of 100 MeV is uniformly incident on the face

Longitudinal segmentation can be used to separate low- and high-energy particles in one event, when the former leave almost all their energy in the first layer.
In addition, in a longitudinally segmented calorimeter it is easier to replace crystals damaged by radiation, since the main damage will occur in the first layer of the calorimeter.

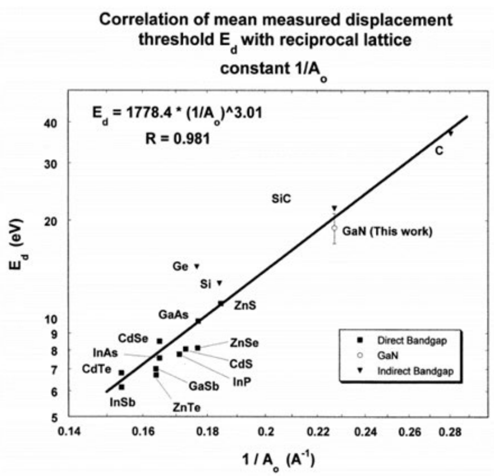
We plan to conduct studies of prototypes longitudinally segmented electromagnetic calorimeters using LYSO and other crystals to determine time and energy resolution.
Low-noise radiation-resistant preamplifier circuits based on discrete GaN elements could be used with such segmented calorimeters.
Research will be carried out using the Linac-200 electron beam and other accelerators.

Radiation resistance of materials and electronics



Yttrium doped BaF_2 light yield loss after irradiation

- In previous years, we carried out a number of works to study the radiation resistance of organic and inorganic scintillators. In particular, when irradiating samples of BaF2 crystals (pure and doped with yttrium) with neutrons, we noticed that the light output loss of the fast component was 2-3% higher than that of the slow component. This effect requires further study.
- Wide-bandgap III-V semiconductors are the most promising materials for the manufacture of radiation-resistant devices. The measured displacement energy value for a GaN atom of 19.2 eV is relatively high compared to other widely used types of semiconductors. A low-noise radiation-resistant front-end preamplifiers for advanced calorimeters with SiPM readout is of interest for many experiments operating in harsh radiation conditions.



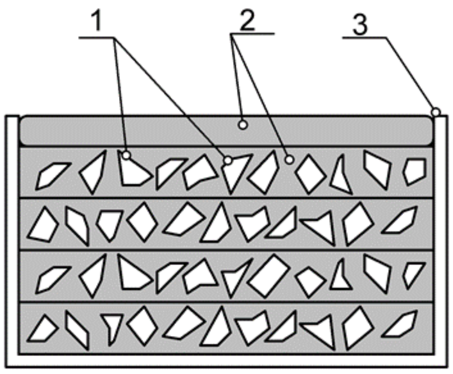
GaN has higher displacement energy and higher radiation hardness

- The design, modelling and fabrication of a low-noise radiation-resistant preamplifier circuit using discrete GaN and GaAs elements for SiPM will be carried out.
- The radiation hardness of the discrete GaN and GaAs elements and preamplifiers will be studied using a neutron beam.
- We plan to continue studying the radiation resistance of pure and yttrium-doped BaF_2 crystals, LYSO crystals, and others of interest.

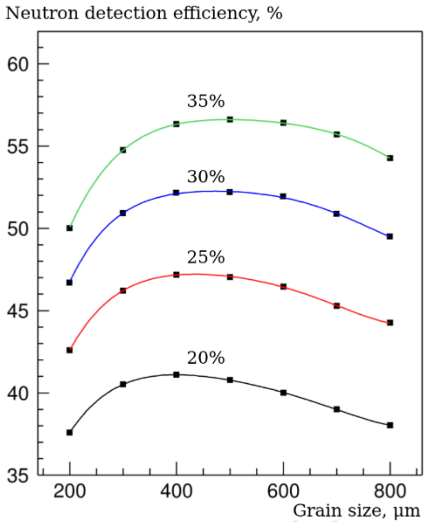
The samples will be irradiated:

- with a neutron beam at the IBR-2M
- with an electron beam at the Linac-200
- with ^{60}Co gamma source (there are several options – in Russia or at the irradiation facilities of our colleagues in Baku (Azerbaijan) or Frascati (Italy)).

New scintillation materials for detecting thermal neutrons



- New composite scintillatorы for detecting thermal neutrons have been developed and studied. Scintillators consist of LiF grains embedded in an optical compound (acrylic resin, epoxy resin, silicone compound)
- Composite scintillators allow to reduce sensitivity to gamma background by almost two orders of magnitude compared to a scintillator made of homogeneous lithium glass while reducing the efficiency of neutron detection to 50%

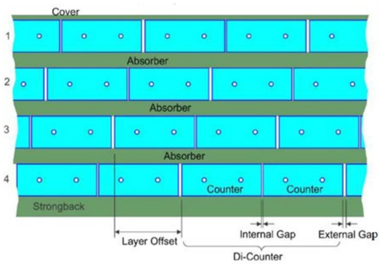


We plan to continue this research for another three years.
During this period it is planned:

- Create new composite scintillators based on crystals of zinc sulfide and boron oxide (all produced in Russia)
- Simulate and optimize the scintillator structure using the GEANT package
- Manufacture and test scintillator samples using neutron beams and gamma radioactive sources

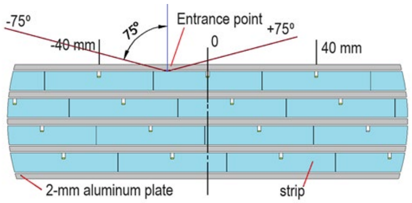
Optimizing the operation of scintillation detector systems

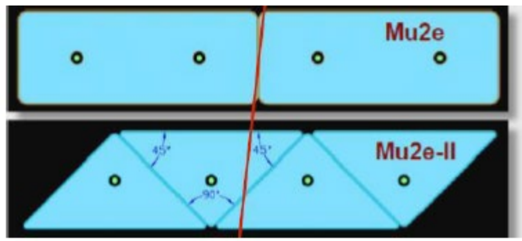
Mu2e



The Cosmic Ray Veto (CRV) systems in the Mu2e and Comet experiments are made of rectangular scintillation strips (two left figures). It is expected that at the next stage of both experiments, with an increase in muon intensity by an order of magnitude, these CRVs will not be able to provide the required efficiency.

Comet





Triangular-shaped scintillators can improve performance and provide the necessary detection efficiency in harsh radiation environments

We plan to:

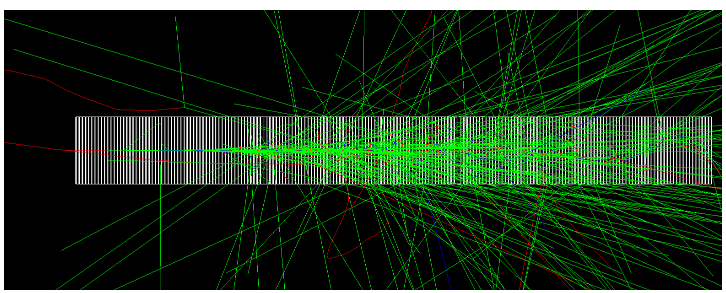
- Study strips of triangular cross-section to evaluate light collection across the strip (transverse scanning) with cosmic muons and with a radioactive sources
- Study the efficiency of a module consisting of four layers of triangular strips using computational methods and compare it with the efficiency of a similar module made of rectangular cross-section scintillation strips
- Build a prototype of CRV module based on triangular cross-section strips and study its parameters

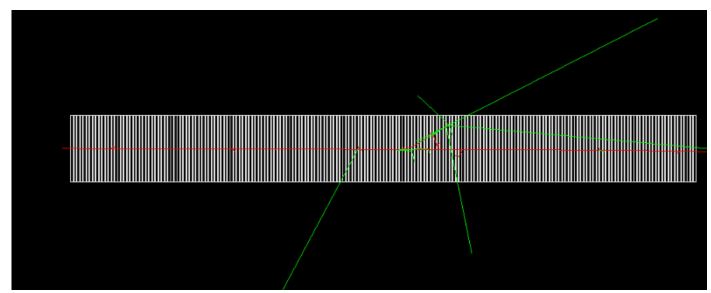
Optimization of “scintillator+SiPM+front-end” system:

- Development of preamps to work with SiPM to obtain time resolution ~ 40-50 ps
- SiPMs of various types and produced by different manufacturers will be tested

Development of analysis and modelling methods of electromagnetic and hadronic calorimeters

- Creation of software for a detailed description of electromagnetic and hadron calorimeters using the GEANT4 package and for modelling their response to electrons and hadrons using modern Monte Carlo generators. The task will be performed for several options of calorimeters for experiments at future colliders.
- Conducting an analysis of simulated data to determine the influence of dead matter in the design of electromagnetic and hadronic calorimeters on the energy resolution and linearity of the calorimeter response.
- Optimization of the design and construction of electromagnetic and hadronic calorimeters based on the results of the conducted research in order to improve their characteristics. Calorimeters for experiments at future colliders will be considered.
- Study of the properties of prototypes and full-scale electromagnetic and hadronic calorimeters depending on the energy, angle of incidence, and pseudo-rapidity of particles with full modelling of proton-proton, proton-deuteron, deuteron-deuteron, proton-nuclear, and nucleus-nucleus interactions in order to develop and implement effective methods of reconstruction of the calorimeter response to particles and jets.





Simulation of the passage of electron (E ~5 GeV) and cosmic muon (right side) through an ECal module
(200 layers of lead 0.5 mm thick and 200 layers of scintillators 1.5 mm thick)

Expected results during the project (1)

1) Technology for microstructural gas detectors of the Micromegas type with a gas gain of more than 20,000, energy resolution up to 20%, spatial resolution up to 200 μm, and well-type (WEM) with a resistive anode coating will be developed. It is planned to develop a method for creating straw detectors with resistive cathodes and readouts from external strips. A manufacturing technology will be developed, and prototypes of straw detectors with a wall thickness less than 12 microns will be created. 2025-2029

2) Prototypes of a sectional electromagnetic calorimeter using LYSO and other types of crystals will be modelled, created, and tested. 2025-2029

3) New data will be obtained on the radiation resistance of crystals used in electromagnetic calorimeters. Electronic circuits will be developed, and low-noise radiation-resistant preamplifiers based on discrete GaN (GaAs) elements for SiPM will be modelled, manufactured, and tested for radiation resistance. 2025-2029

4) Simulation of a muon system based on triangular cross-section scintillators will be carried out, prototypes will be created and investigated, and their parameters will be compared with the parameters of similar systems with rectangular cross-section scintillators. 2025-2028

5) An optimization will be carried out, and a “scintillator + SiPM + front-end electronics” system with high speed and a time resolution of 40-50 ps will be created. 2025-2028

Expected results during the project (2)

6) New heterogeneous detectors will be developed to detect thermal neutrons with sensitivity to gamma rays suppressed by 2-3 orders of magnitude. 2025-2027

7) The design will be developed, prototypes of electromagnetic calorimeter modules will be created, they will be studied with cosmic muons and on accelerator beams, and test results will be studied in comparison with predictions of Monte Carlo models for prototypes and full-scale electromagnetic calorimeter modules. For this purpose, software will be developed for Monte Carlo simulation and analysis of experimental data for prototypes and full-scale modules of electromagnetic calorimeters for planned experiments at future accelerators (STCF, CEPC). 2025-2029

8) The properties of prototypes and full-scale electromagnetic and hadron calorimeters will be studied depending on the energy, angle of incidence, and pseudo-rapidity of particles with full simulation of proton-proton, proton-deuteron, deuteron-deuteron, proton-nuclear, and nucleus-nucleus interactions in order to develop and implement effective methods for reconstructing the calorimeter response to particles and jets under future experimental conditions. 2025-2029

9) Simulated data will be analyzed to determine the amounts of dead matter in the design of electromagnetic and hadronic calorimeters and their impact on the energy resolution and linearity of the response of calorimeters for experiments at future accelerators (STCF, CEPC). 2025-2029

Project participants

Participating laboratories: DLNP, VBLHEP, FLNP

Total FTE for young group members: 6.1

We expect to have 1-2 master students each year (not yet included in the table)

It is expected that there will be more participating organizations in the future

Organisation	Country	Participants
IP NASB	Minsk, Belarus	Kurochkin Yu.A. +3
INP BSU	Minsk,Belarus	Misevich O.V. +3
IE NASB	Minsk,Belarus	Baev V. +3
IP, Min. Science and Education	Baku, Azerbaijan	Nagiev S. +3
SamSU	Samarkand, Uzbekistan	Safarov A.N.+3
LNF	Frascati, Italy	Miscetti S. +5

№	Category	NAME	Division	Position	FTE
1.	Scientists	Davydov Yu.I.	DLNP	Head of dept.	0.7
2.		Artikov A.M.	DLNP	Head of sector	0.8
3.		Atanov N.V.	DLNP	Researcher	0.7
4.		Atanova O.S.	DLNP	Junior researcher	0.7
5.		Afanaciev K.G.	DLNP	Researcher	0.8
6.		Baranov V.Yu.	DLNP	Researcher	0.8
7.		Boikov A.V.	DLNP	Junior researcher	0.6
8.		Vasilyev I.I.	DLNP	Researcher	0.7
9.		Gritsay K.I.	DLNP	Researcher	0.3
10.		Guseinov N.A.	DLNP	Senior researcher	0.7
11.		Zimin I.Yu.	DLNP	Researcher	0.8
12.		Kiseeva V.I.	DLNP	Junior researcher	0.7
13.		Krylov V.A.	DLNP	Researcher	0.3
14.		Kravchuk N.P.	DLNP	Senior researcher	0.8
15.		Kulchitsky Yu.A.	DLNP	Head of sector	0.5
16.		Kuchinsky N.A.	DLNP	Senior researcher	0.7
17.		Malyshev V.L.	DLNP	Researcher	0.7
18.		Plotnikova E.M.	DLNP	Researcher	0.5
19.		Simonenko A.V.	DLNP	Senior researcher	0.8
20.		Suslov I.A.	DLNP	Senior researcher	0.5
21.		Tereshko P.V.	DLNP	Researcher	0.5
22.		Tropina A.I.	DLNP	Junior researcher	0.7
23.		Khomutov N.V.	DLNP	Researcher	0.6
24.		Chokheli D.	DLNP	Senior researcher	0.4
25.		Bulavin M.V.	FLNP	Head of sector	0.1
26.		Enik T.L.	VBLHEP	Head of group	0.1
27.		Kolesnikov A.O.	VBLHEP	Head of service	0.1
28.		Movchan S.A.	VBLHEP	Head of sector	0.1
29.	Engineers	Kuzmin E.S.	DLNP	Senior engineer	1.0
30.		Moskalenko V.D.	DLNP	engineer	1.0
31.		Rogozin V.A.	DLNP	engineer	1.0
32		Shalyugin A.N.	DLNP	Senior engineer	0.8
	Total:				**19.5**

SWOT analysis

Strengths of the project:

- Expertize in developing of various types of innovative detectors and electronics and experience in their use in experiments by group members
- Extensive experience in simulation methods, development of software and implementation of machine learning in data analysis
- Existing of own certified laboratory for testing detectors with radioactive sources
- Availability of accelerator test beams and a neutron beam (IBR-2M) at JINR

Weakness of the project:

We expect high competition for the beam at Linac-200 when it will be available

Opportunities:

The project provides for a prominent role for young scientists and the opportunity to prepare and defend candidate and master's theses.

Threats:

The current situation may affect the ability to acquire the necessary materials and equipment to complete some project tasks.

Resource request

We are asking for 400 k$ for 5 years

- Purchase of electronic components, electronic modules
- Purchase of crystals and plastic scntillators, WLS fibers
- Purchase of materials for detectors development
- Computers, software and technical support for MC simulation, processing and analysis of experimental and simulated data
- International cooperation

- ~150 hours/year of an accelerator beam time (about 20 days with 8-hour shift)
- ~ 300 hours/year IBR-2M irradiation time (one cycle of IBR-2M)

Names of costs, resources, sources of funding			**Cost (thousands of dollars) resource requirements**	**Cost, distribution by year**				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation (IC)	100	20	20	20	20	20
		Materials	300	80	70	60	45	45
		Equipment and third-party services (commissioning)						
		Commissioning work						
		Services of research organisations						
		Acquisition of software						
		Design/construction						
		Service costs						
Resources required	**Normo-hours**	Resources						
		the amount of FTE,						
		accelerator	750	150	150	150	150	150
		– reactor,….	1500	300	300	300	300	300
Sources of funding	**Budgetary resources**	JINR budget *(budget items)*	400	100	90	80	65	65
	Extrabudgetary (suppl. estimates)	Contributions by co-contractors Funds under contracts with customers Other sources of funding						

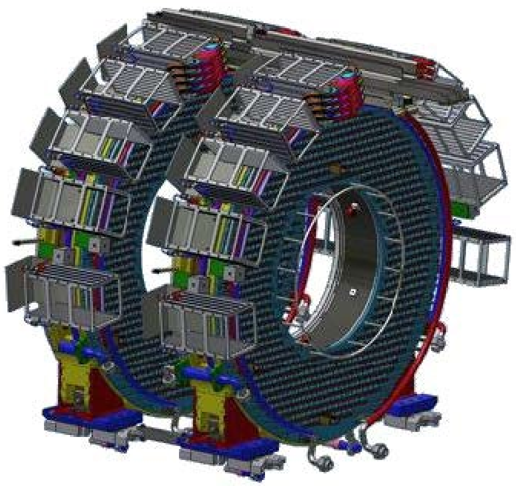
If the PAC makes a positive decision on the project, it will be opened in a new theme “Hadronic and rare leptonic processes, development of advanced detectors and analysis methods”

We ask the PAC to support the opening of a new project “Development of a particle registration technique in future experiments with the participation of JINR” and a new theme “Hadronic and rare leptonic processes, development of advanced detectors and analysis methods”

Thank you for the attention!!!

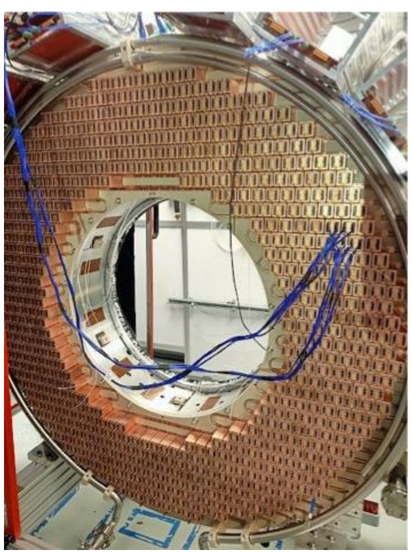
Backup slides

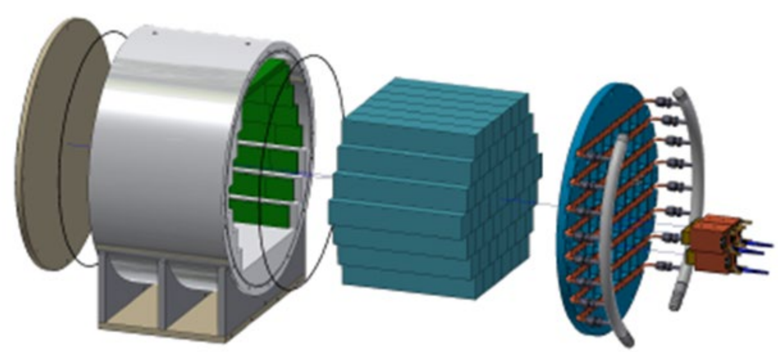
Electromagnetic calorimeter of Mu2e



JINR along with LNF (Frascati, Italy) and Caltech (Pasadena, USA) played leading role in development ECal

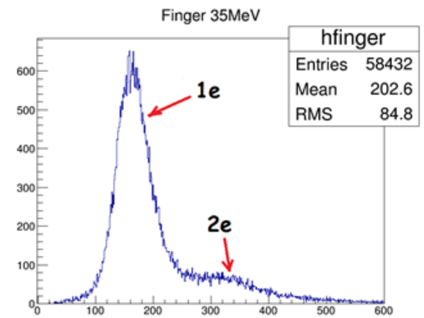
- Tests of individual crystal of different types (LYSO, BaF2, CsI) were carried out at JINR, LNF and Caltech
- The 5x5 LYSO array was tested in an electron beam at Frascati and a photon beam at Mainz
- 3x3 CsI arrays were tested in electron beams in Frascati and Yerevan (Armenia)
- Module-0 (51 crystals, 102 SiPMs, 102 FEE boards) with pre-productions and mechanics cooling systems similar to the final ones tested at Frascati
- Development of front-end electronics and QC of all channels in Dubna



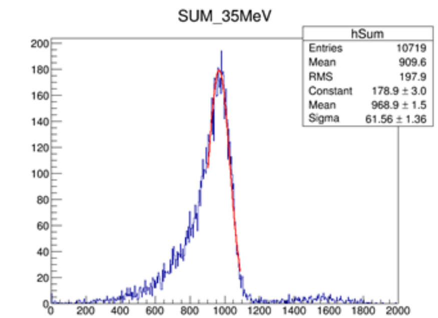


Mu2e ECal: tests of 3x3 arrays in Frascati and Yerevan

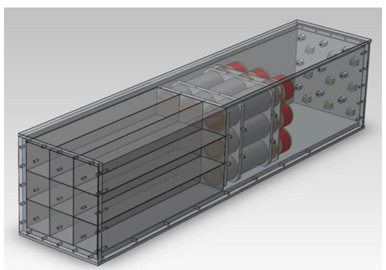
- 80-120 MeV electron beam in Frascati and 15-35 MeV beam in Yerevan
- Pure CsI crystals 30x30x200 mm and 34x34x200 mm produced by ISMA, Kharkov
- Time and energy resolutions were obtained that meet the requirements of the experiment ($\sigma_T \sim$ 110 ps and $\sigma_E \sim 6.5\%$ at 100 MeV)



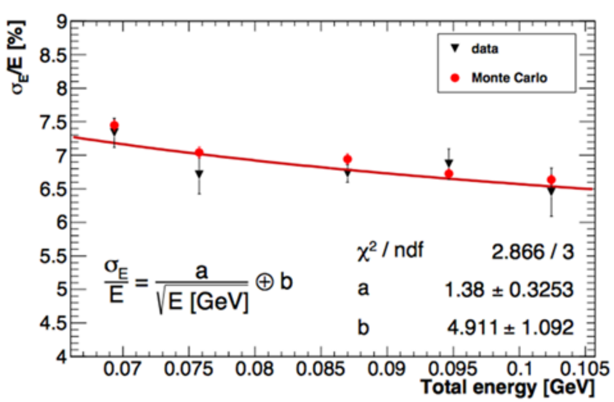
Trigger counter



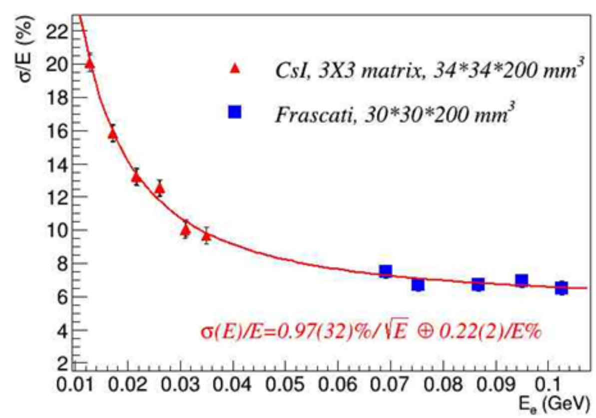
Spectrum from array at 35 MeV



Energy resolution:

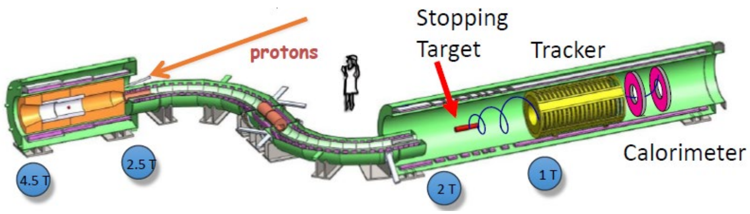


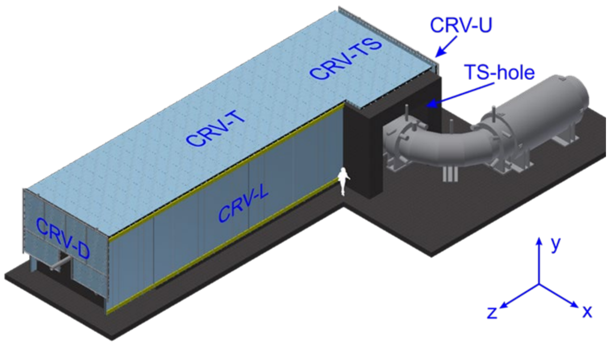
result from Frascati

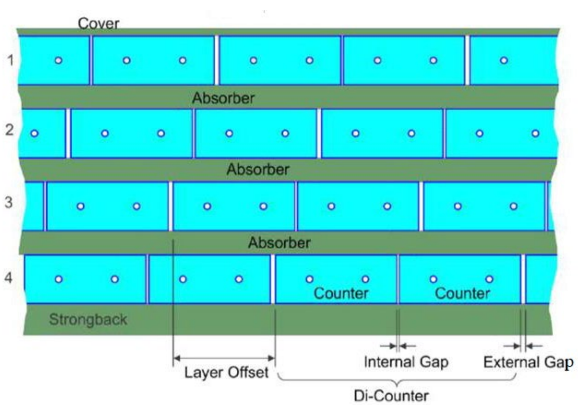


Joint Frascati-Yerevan fit

Mu2e CRV system





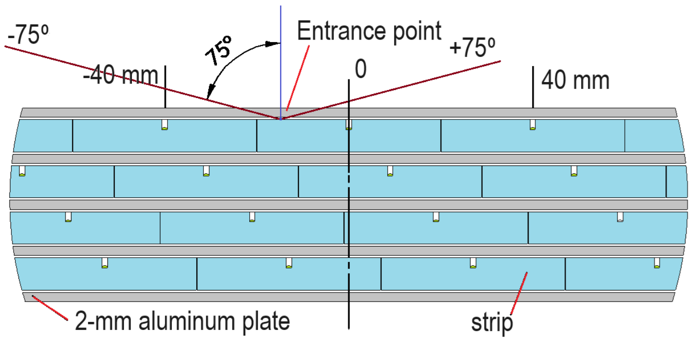


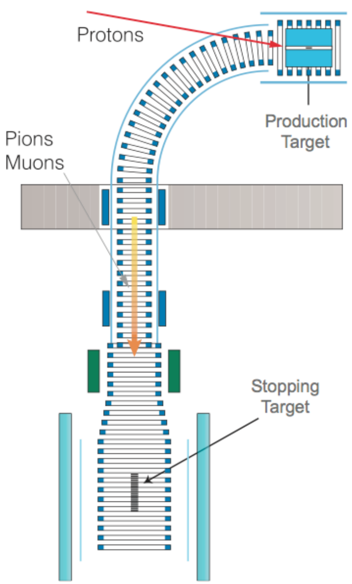
JINR and University of Virginia at Charlottesville played leading role in the CRV development:

- simulation of CRV operation
- design driven by need for excellent efficiency, large area, small gaps, high background rates, access to electronics, and constrained space
- fabrication of prototypes of CRV modules and their testing on beams at Fermilab
- development and demonstration a technology for filling fiber holes in scintillators with liquid silicone synthetic rubber to increase light collection up to 50%
- development of all stages of assembly and testing of CRV modules during their mass production
- fabrication of the pilot CRV modules (start of mass production) began just before pandemic

First CRV module for Comet

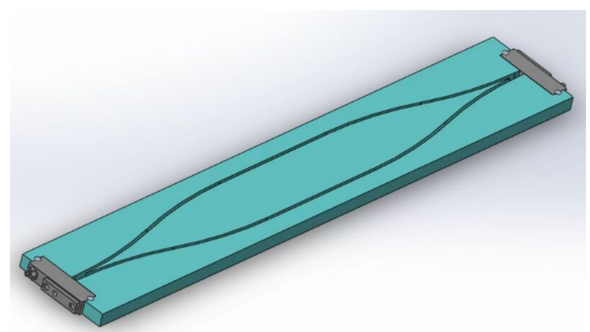
Cross-section of CRV module





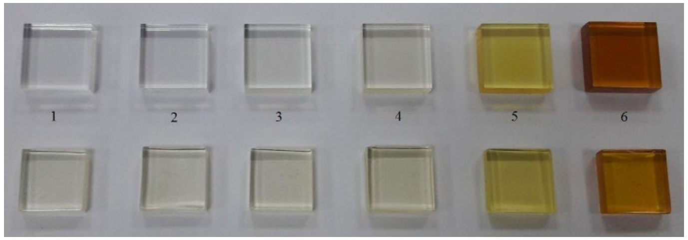
Some time ago our colleagues from the JINR Comet group asked us to help with the creation of the CRV module for the Comet experiment.

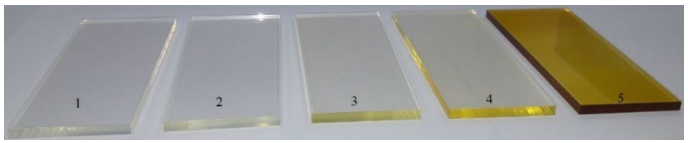
Members of our group designed a module based on scintillation strips from the Uniplast company (Vladimir city) and built the first CRV module for the Comet experiment.
The CRV module was shipped to J-PARC (Japan), where members of our group again helped to start testing measurements with cosmic muons.



Shape of a single strip

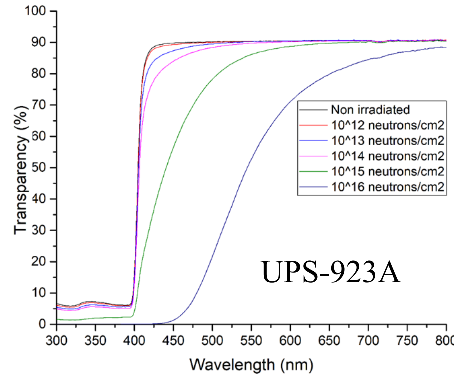
Radiation studies of scintillators

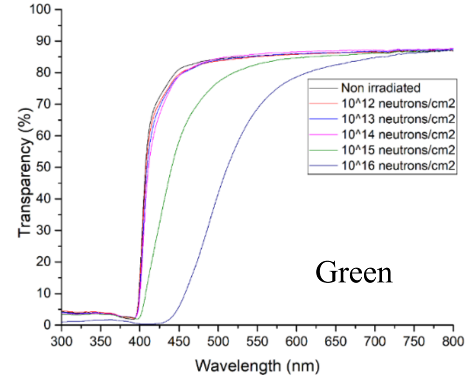




UPS-923A: polystyrene, 2% PTP, 0.03% POPOP
Green: polystyrene, single fluor dopant 3HF (3-hydroxyflavone)

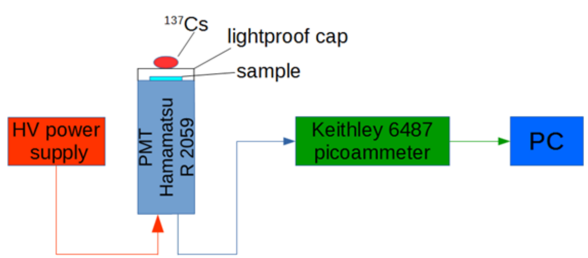
- Studies have been carried out on the radiation resistance of inorganic scintillators
- Scintillator samples were irradiated with neutrons at IBR-2M

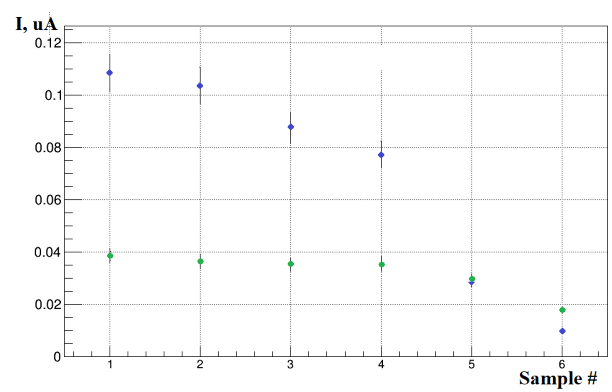




Transparency of samples after irradiation

Sample #	Fluence, n/cm²
1	Non-irradiated
2	~10^{12}
3	~10^{13}
4	~10^{14}
5	~10^{15}
6	~10^{16}



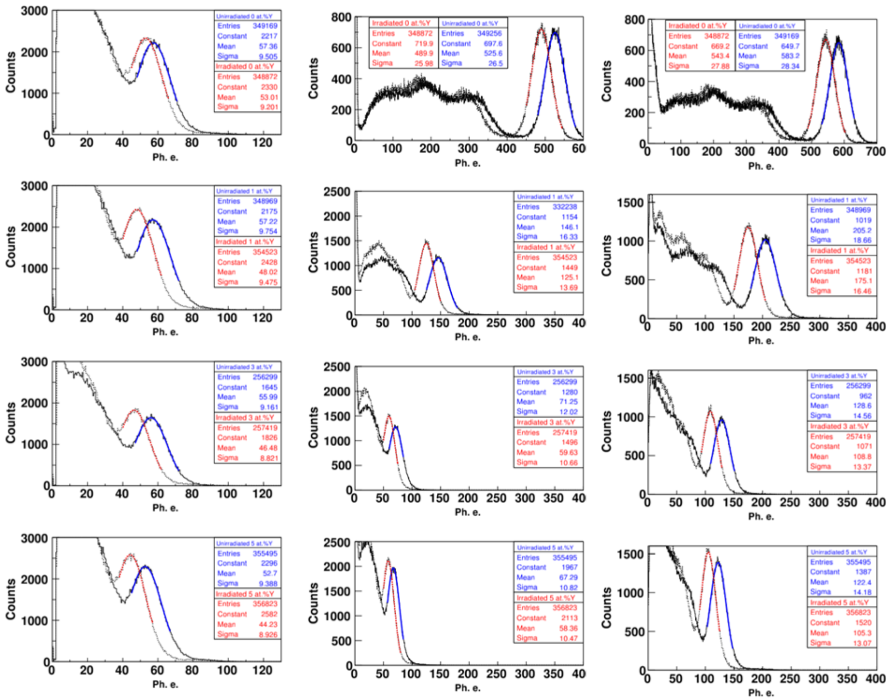


Light output of irradiated samples

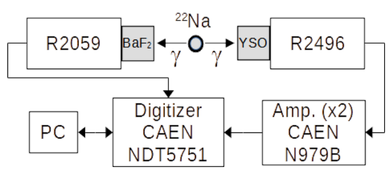
Radiation studies of BaF_2 crystals

Crystals (1x1x1 cm^3, SICCAS) BaF_2 pure and doped with yttrium (1 at.%Y, 3at.%Y and 5at.%Y) were irradiated on IBR-2M

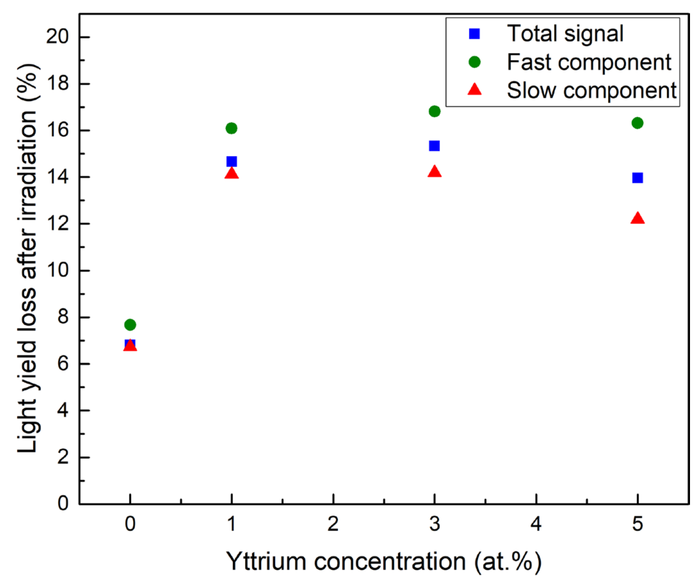
Fast Slow Total



Fast, slow and total spectra due to irradiation by ^{22}Na gamma source

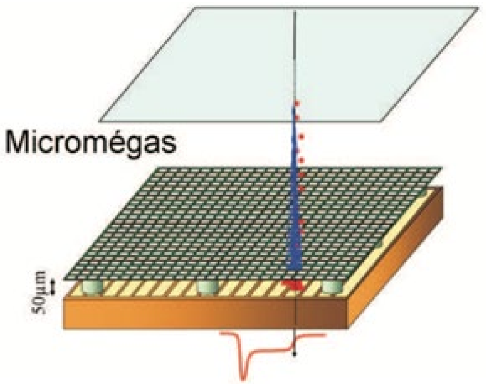


- After irradiation, the loss of light output is the smallest for pure BaF2
- The loss of light output for yttrium-doped samples is almost 2 times higher than for pure BaF2
- In all yttrium-doped samples after irradiation, the loss of light output of the fast component is 2-3% higher than that of the slow component. This requires further research

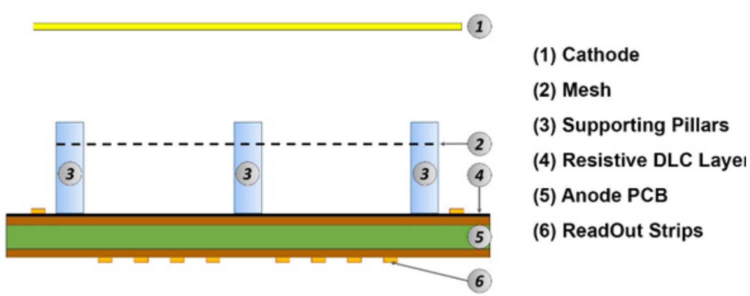


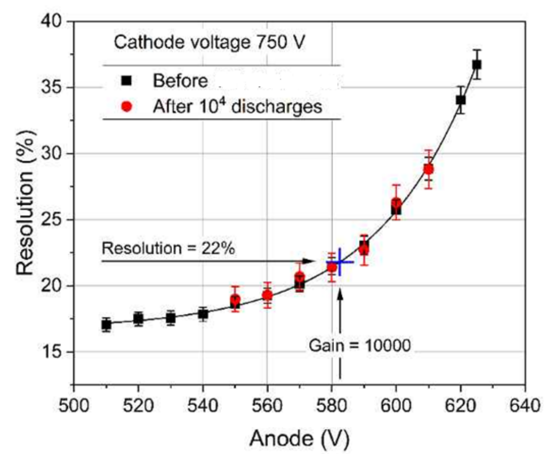
Gas detectors with resistive elements

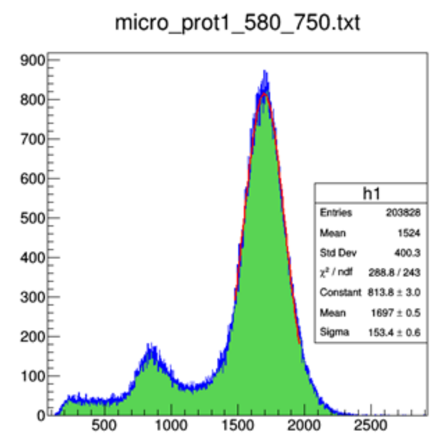
Research is being carried out to create and test various types of gas detectors with resistive elements and coatings based on diamond-like carbon (DLC):



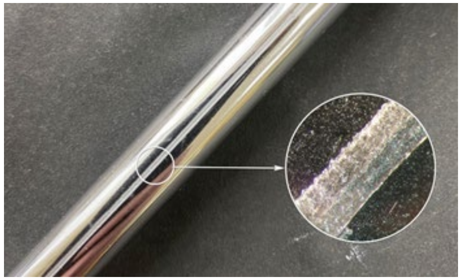
- Micromegas and GEM Well-type microstructured gas detector prototypes with a resistive anodic coating were developed and tested and demonstrated their high breakdown resistance
- The first samples of thin-walled drift straw tubes with a resistive cathode and external strip readout were manufactured and tested

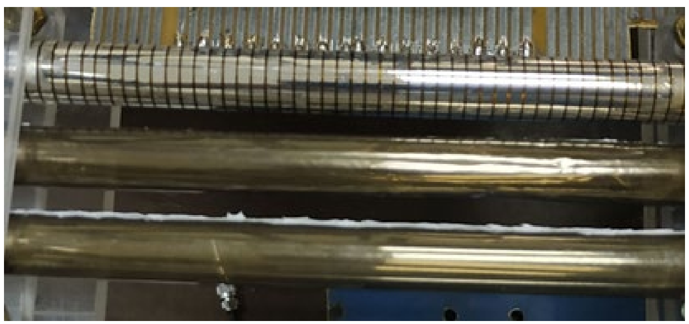




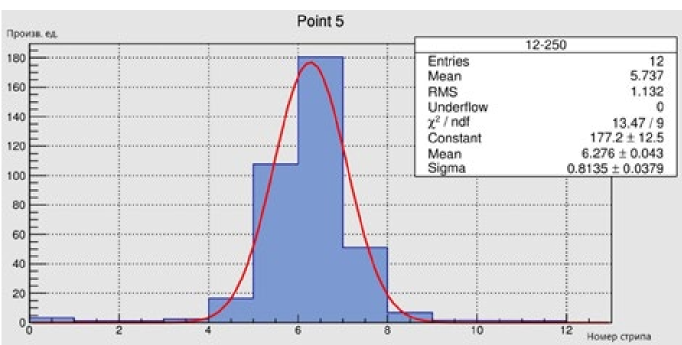


Straw tubes with cathode readout

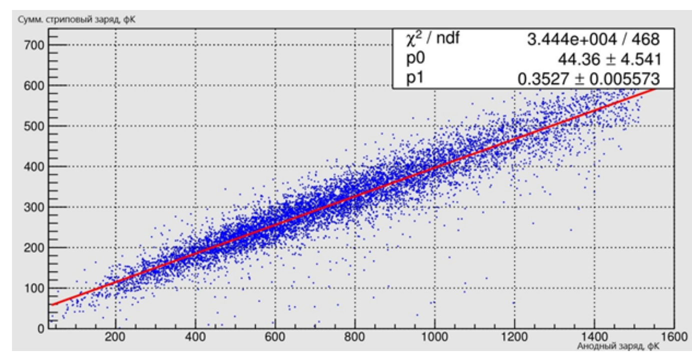




- The first samples of thin-walled drift straw tubes with a resistive cathode and external strip readout were manufactured and tested
- Wide range of surface resistances (from 100 kΩ to GΩ per square)
- Thin-walled straw tubes are made using ultrasonic welding technology from Mylar film
- The resistive DLC coating was applied to the Mylar film using vacuum cathode arc deposition, the resistance is about 10 MΩ/square



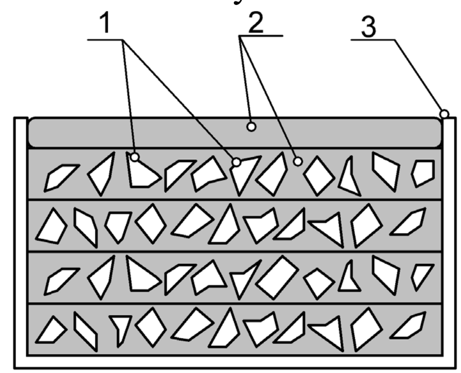
Distribution of signals from strips



Linearity of signals from the wire and strips

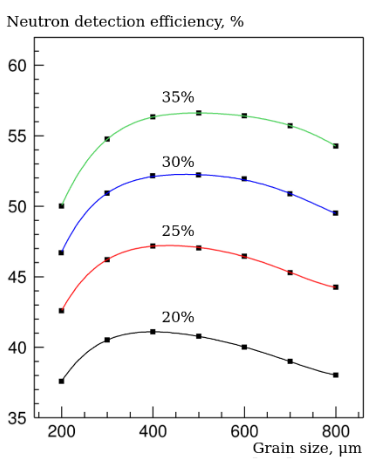
Heterogeneous scintillators based on lithium glass

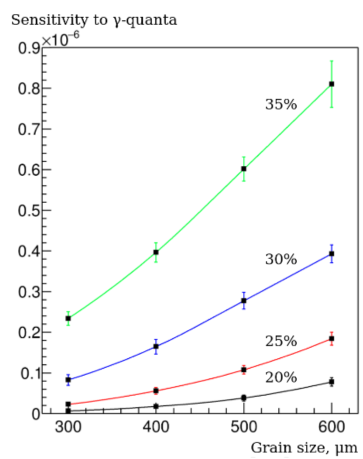
The goal of these studies was to develop a heterogeneous scintillator for detecting thermal neutrons based on lithium glass with the selection of the optimal structure to minimize the gamma sensitivity of the detector while maintaining high neutron efficiency

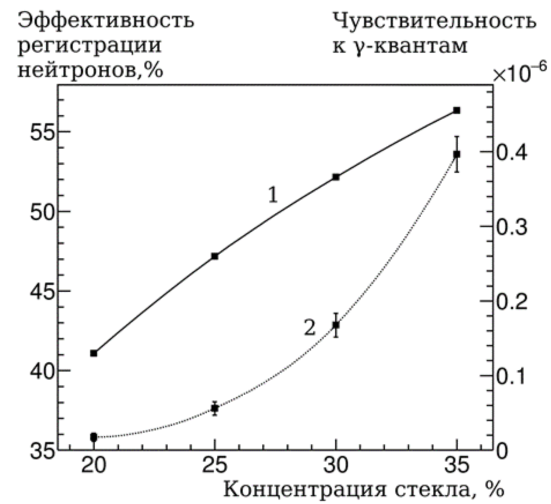


- The fragments of the heterogeneous scintillator were in the form of NE 912 lithium glass cubes.
- Calculations were carried out for cubes with face sizes from 200 to 800 μm with a step of 100 μm.
- Lithium glass concentrations from 20 to 35% relative to the total volume of the heterogeneous scintillator were considered.
- Optical compounds – silicone, acrylic, epoxy resin

Modeling the response of heterogeneous scintillators:

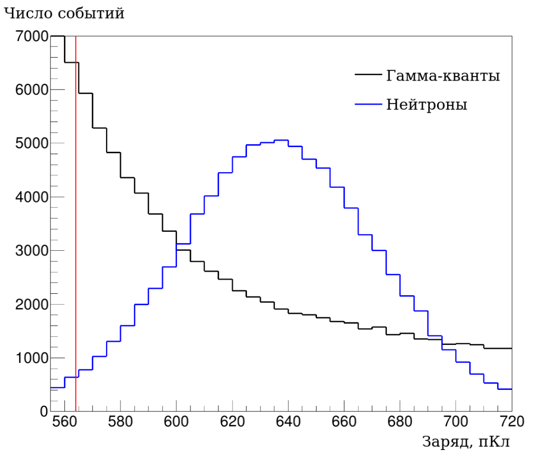






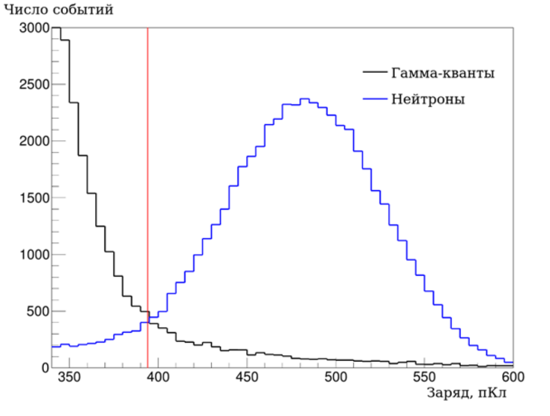
Heterogeneous scintillators: measurement results

- The efficiency of neutron detection by heterogeneous scintillators depends on the glass concentration and is about 50-55%
- The gamma sensitivity of heterogeneous scintillators is suppressed by approximately 2 orders of magnitude compared to lithium glass
- Composite structure is a better method for neutron/gamma discrimination compared to electronic signal selection methods



Gamma sensitivity of heterogeneous scintillators
(Gamma sensitivity of lithium glass $(1.42 \pm 0.05) \cdot 10^{-4}$)

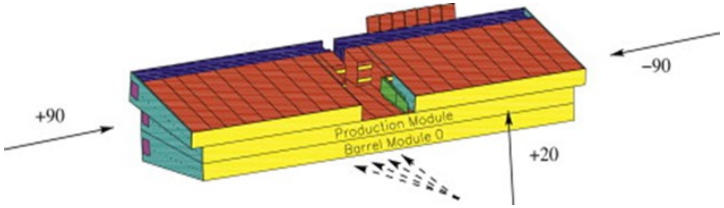
	Epoxy	Silicone compound	Acrylic
25%	$(9{,}25 \pm 0{,}13) \cdot 10^{-6}$	$(1{,}35 \pm 0{,}11) \cdot 10^{-6}$	$(0{,}53 \pm 0{,}05) \cdot 10^{-6}$
30%	$(13{,}3 \pm 0{,}2) \cdot 10^{-6}$	$(2{,}65 \pm 0{,}08) \cdot 10^{-6}$	$(6{,}04 \pm 0{,}08) \cdot 10^{-6}$
35%	$(22{,}5 \pm 0{,}2) \cdot 10^{-6}$	$(4{,}90 \pm 0{,}13) \cdot 10^{-6}$	$(13{,}8 \pm 0{,}2) \cdot 10^{-6}$



Developed methods for studying the properties of calorimeters

- A precision non-parametric method for measuring energy in a calorimetric complex, which made it possible to achieve record energy linearity.
- A method for measuring the non-compensation of an electromagnetic calorimeter, which made it possible to measure the amount of non-compensation for the ATLAS liquid-argon electromagnetic calorimeter
- A method for three-dimensional parameterization of a hadron shower, which made it possible to measure the radial energy density of a hadron shower depending on its longitudinal coordinate
- Method for describing the longitudinal density of a hadron shower in a combined calorimeter
- A method was developed and, on its basis, electromagnetic calibration of hadron calorimeter modules was carried out in electron beams with energies from 10 to 350 GeV, which made it possible to establish the energy scale of the calorimeter with excellent accuracy
- A modification of the local hadronic calibration method for combined calorimeters was developed, which made it possible to obtain record energy resolution and linearity for the created calorimetric complex
- A neural network method for calculating energy losses in the dead matter of the calorimetric complex was developed and applied in the analysis of experimental data, which made it possible to significantly improve the energy resolution of the calorimetric complex
- Experimental studies of the linearity, energy resolution, non-compensation, and leakage of the hadron shower beyond the hadronic and combined (electromagnetic and hadronic) calorimeters were carried out in beams of electrons, muons, pions and protons with energies from 3 to 350 GeV at the SPS accelerator

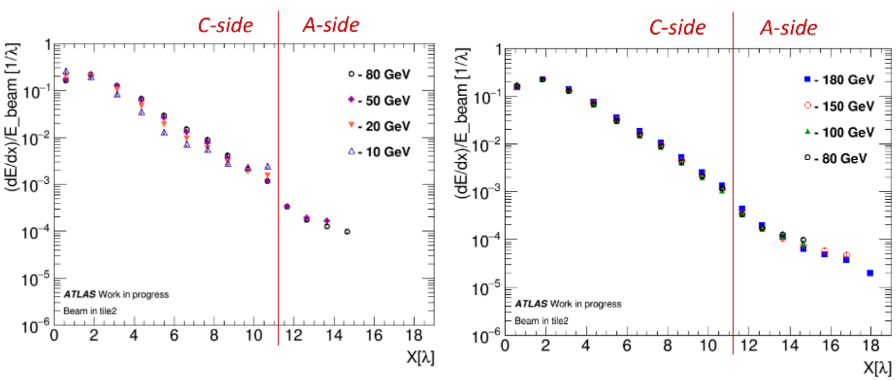
Study of hadron jet profiles



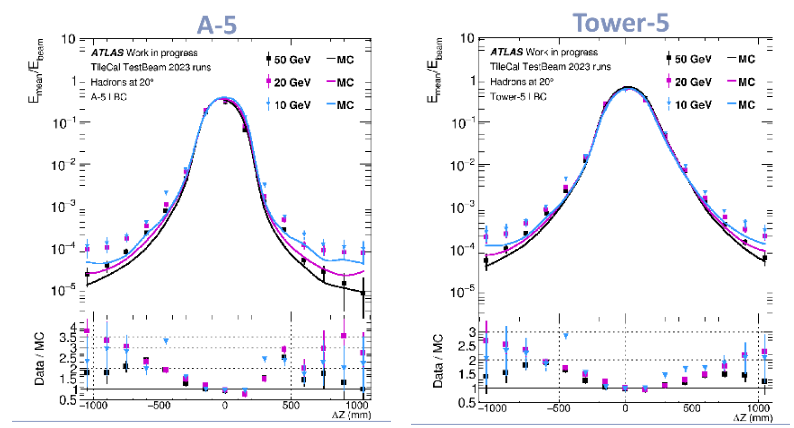
hadronic tile calorimeter modules during test studies

The study was carried out using ECAL and TileCal calorimeters. The purpose of the research was to study the profile of the longitudinal and transverse shape of the development of a hadron shower using hadron beams incident at an angle of 90 degrees and 20 degrees, comparison with Geant4 models and their validation

Longitudinal profile of a hadron shower

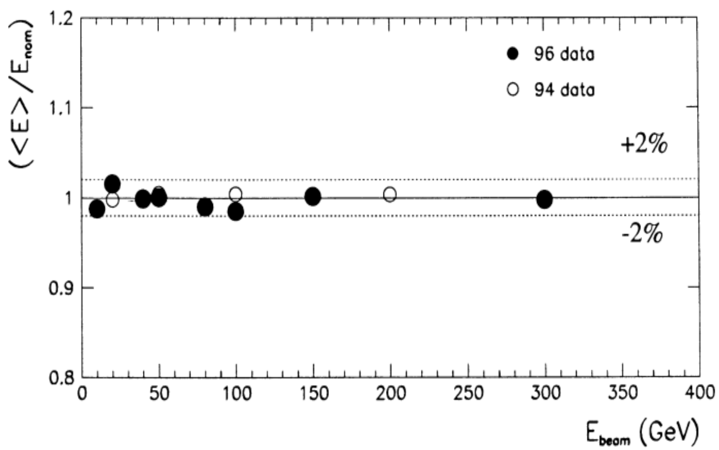


Transverse profile of a hadron shower at 20 deg.

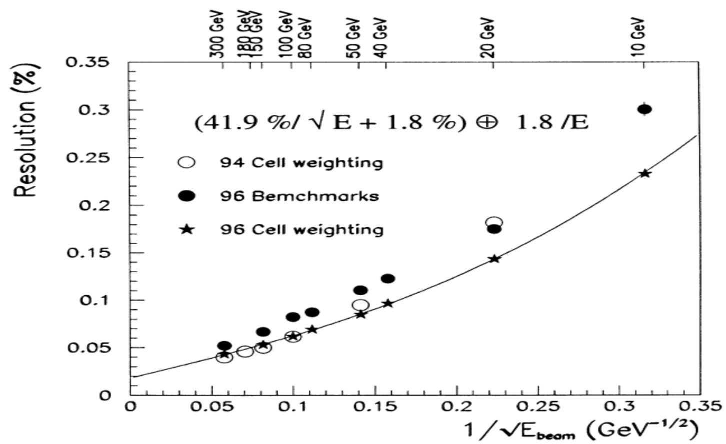


Studies of the combined ATLAS calorimeter

Joint tests of prototypes of an electromagnetic liquid argon calorimeter and a hadronic scintillation calorimeter were carried out at SPS (CERN). The energy resolution of pions in the energy range from 10 to 300 GeV at an angle of incidence of about 12˚ is well described by the given expression. During the research, the profiles and leakage of showers, the angular resolution of hadron showers were studied.



Linearity of response VS energy

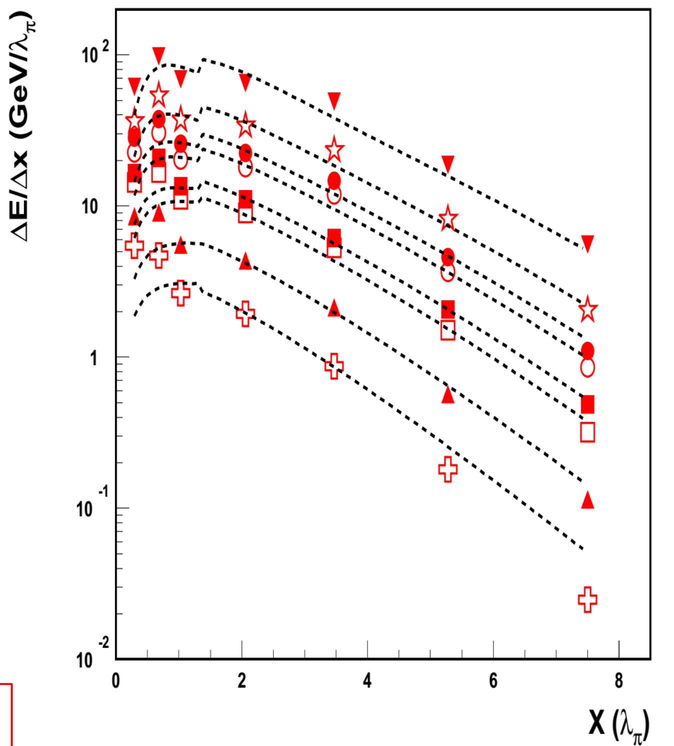


The energy resolution of pions was obtained by the cell weighing method. The results are compared with those obtained using the reference method

Description of the development of a hadron shower

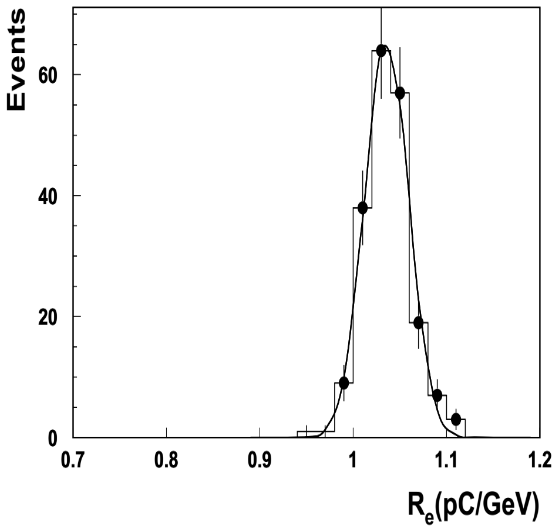
- The transverse and longitudinal profiles of hadron showers recorded by the prototype tile calorimeter and the ATLAS combined calorimeter were studied
- By scanning a pion beam near an energy of 100 GeV, a detailed picture of the behavior of the transverse shower was obtained
- Восстановлены основные плотности радиальной энергии для четырех сегментов по глубине и для всего калориметра
- A three-dimensional parametrization of the hadron shower has been developed

$$\frac{dE(x)}{dx} = N\left\{\frac{wX_o}{a}\left(\frac{x}{X_o}\right)^a e^{-b\frac{x}{X_o}}{}_1F_1\left(1,a+1,\left(b-\frac{X_o}{\lambda_I}\right)\frac{x}{X_o}\right) + \frac{(1-w)\lambda_I}{a}\left(\frac{x}{\lambda_I}\right)^a e^{-d\frac{x}{\lambda_I}}{}_1F_1\left(1,a+1,-(1-d)\frac{x}{\lambda_I}\right)\right\}$$



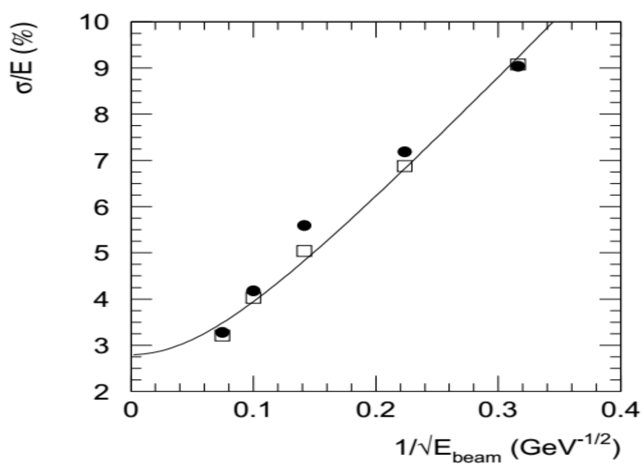
Longitudinal profiles of hadron showers for the ATLAS combined calorimeter with pion energies from 20 to 300 GeV

Electromagnetic calibration of the ATLAS TileCal



Electromagnetic calibration constants for electrons at 20˚

- In order to establish the electromagnetic scale and understand the operation of the TileCal calorimeter in relation to electrons, the modules were irradiated with electron beams with energies from 10 to 180 GeV
- The resulting electromagnetic calibration constants were included in the TileCal calibration database



Energy resolution of electrons at 20˚