Participation in physics research and development of detectors for elementary particle physics: the experience of the JINR group

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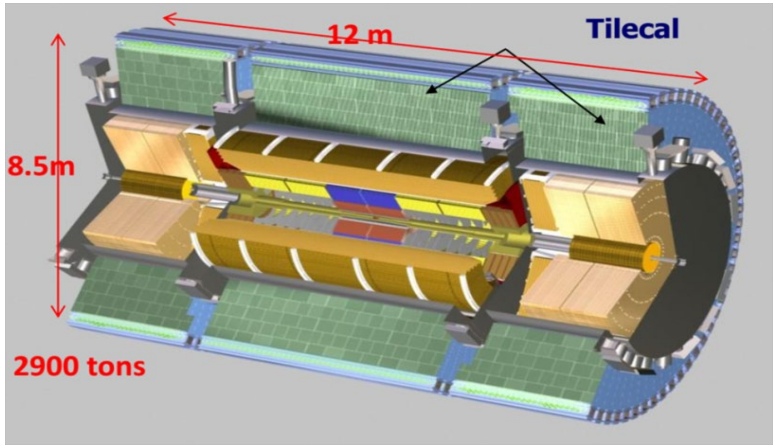
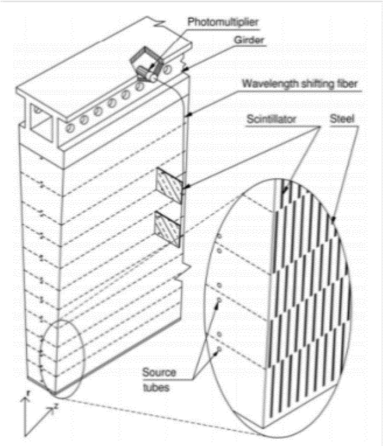
Outline

- Development of ATLAS TileCal and LAr Ecal calibration methods
- Crystal electromagnetic calorimeters
- Stand tests of crystals. Radiation hardness measurements
- Tests of scintillation strips. Cosmic Ray Veto system
- Microstructural gas detectors
- Facilities for R&D at JINR:Linac-200, IBR-2M reactor

ATLAS Tile Calorimeter

JINR made a key contribution to the design of the Tile calorimeter detector, mass production of modules, assembly in the cavern, and commissioning of the hadron tile calorimeter of the ATLAS experiment at the LHC

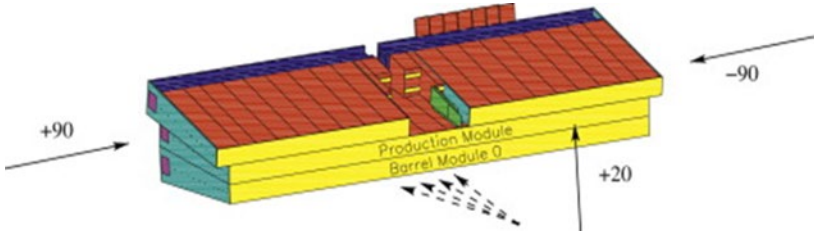


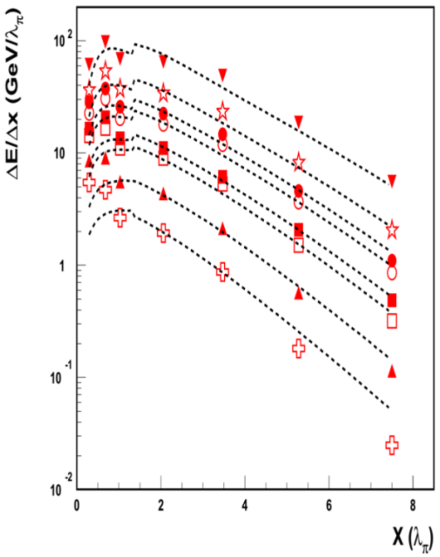


- A series of detailed studies of the characteristics of the prototype and real modules of the hadron tile calorimeter as well as together with the electromagnetic liquid-argon calorimeter – a combined calorimeter were carried out, under irradiation with beams of pions, protons, electrons, and muons with energies from 3 to 350 GeV of the SPS accelerator (CERN)
- 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

V. Batusov, Yu. Budagov, Y. Kulchitsky et al. *ATLAS hadron tile calorimeter: Experience in prototype construction and module mass production; Part. Nucl. 37 (2006) 785-806.*
P. Adragna et al. *The ATLAS hadronic tile calorimeter: From construction toward physics; Trans. Nucl. Sci. 53 (2006) 1275-1281.*
ATLAS Tile Calorimeter Collaboration. *Mechanical construction and installation of the ATLAS tile calorimeter; JINST 8 (2013) T11001.*

Description of the development of a hadron shower





Longitudinal profile of a hadron shower in the combined calorimeter of the ATLAS experiment for pions with energies from 20 to 300 GeV

- The transverse and longitudinal profiles of hadron showers recorded by the prototype calorimeter and the combined calorimeter ATLAS were studied
- Using detailed scanning with a pion beam at an energy of 100 GeV, a detailed picture of the behaviour of the transverse and longitudinal profiles of the hadron shower was obtained
- A formula was derived to describe the hadron shower from the beginning of the calorimeter:

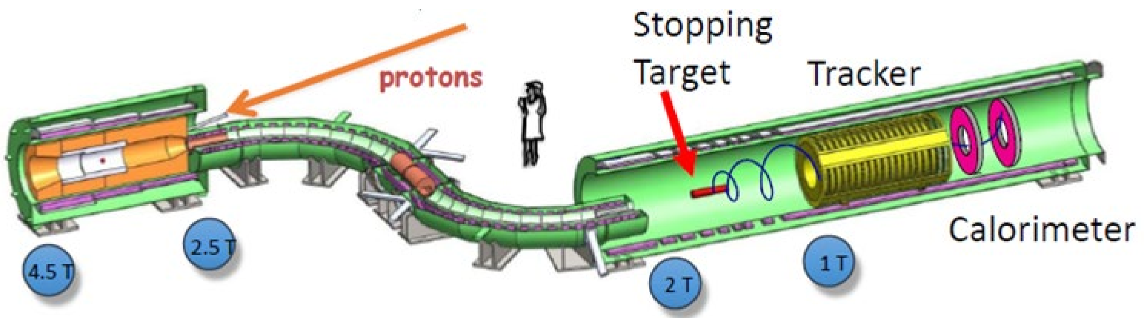
$$\frac{dE(x)}{dx} = N\left\{\frac{wX_o}{a}\left(\frac{x}{X_o}\right)^a e^{-b\frac{x}{X_o}}{}_1F_1\left(1, a+1, \left(b-\frac{X_o}{\lambda_I}\right)\frac{x}{X_o}\right) + \frac{(1-w)\lambda_I}{a}\left(\frac{x}{\lambda_I}\right)^a e^{-d\frac{x}{\lambda_I}}{}_1F_1\left(1, a+1, -(1-d)\frac{x}{\lambda_I}\right)\right\}$$

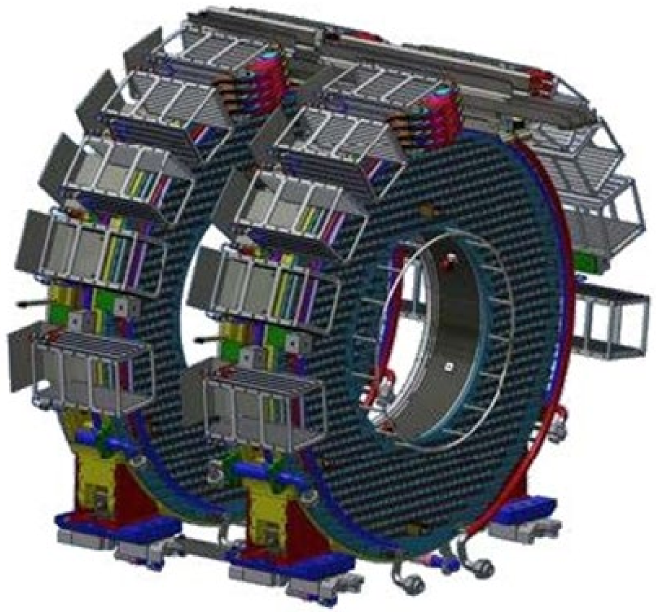
Y. A. Kulchitsky, V. B. Vinogradov. *Analytical representation of the longitudinal hadronic shower development. NIM A413 (1998) 484-486.*
ATLAS TileCal Collaboration. *Hadronic shower development in iron scintillator tile calorimetry. NIM A443 (2000) 51-70.*
ATLAS Collaboration. *Hadron energy reconstruction for the ATLAS calorimetry in the framework of the non-parametrical method, NIM A480 (2002) 508-523.*
ATLAS Collaboration. *Measurement of pion and proton response and longitudinal shower profiles up to 20 nuclear interaction lengths with the ATLAS tile calorimeter. NIM A 615 (2010) 158-181.*

Developed analysis and modelling methods

- 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

Mu2e electromagnetic calorimeter



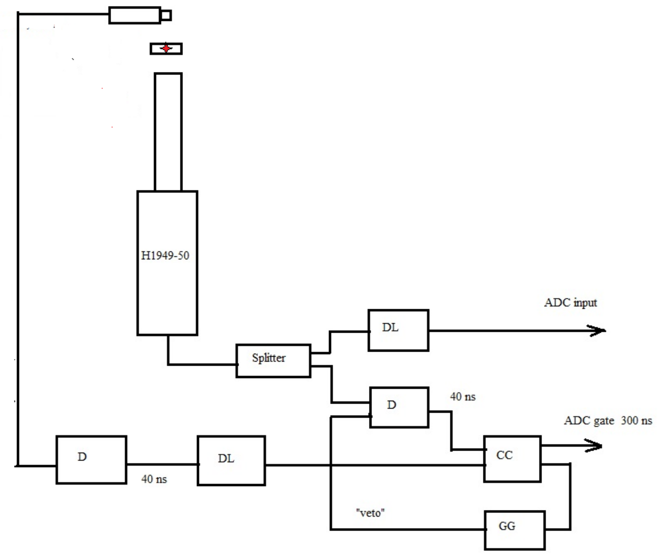


- LYSO:Ce, CsI (purecrystals have been studied for use in ECal
- Tests of individual crystals of different types (LYSO, BaF2 (pure and yttrium doped), CsI (pure)) were carried out at JINR, LNF and Caltech
- Prototypes of ECal were tested with cosmics and at accelerators in Frascati, Erevan, Mainz

Three LYSO crystals

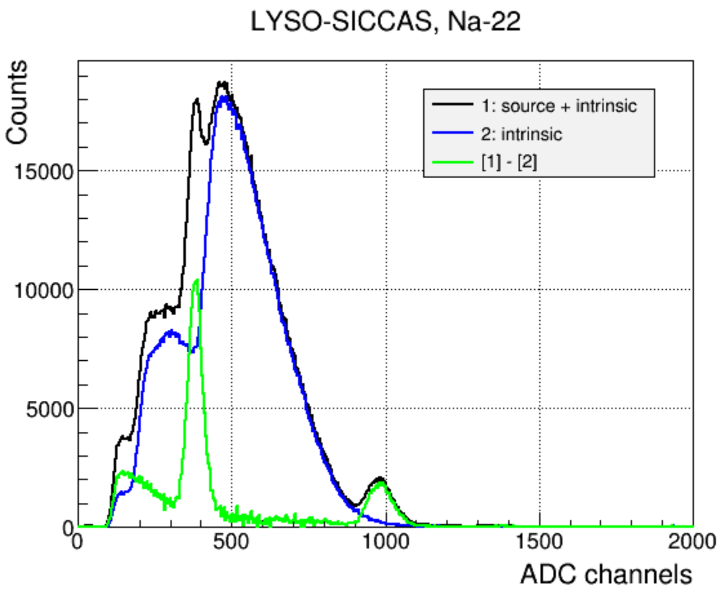
3 crystals have been tested:

- LYSO from SICCAS: 30x30x150 mm^2
- LFS from Zecotek: 30x30x130 mm^2
- PreLude 420 (LYSO) from Saint-Gobain: 30x30x130 mm^2

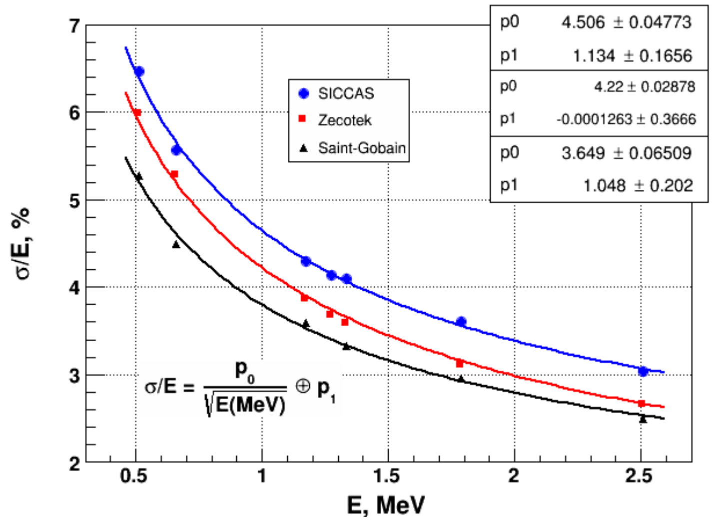


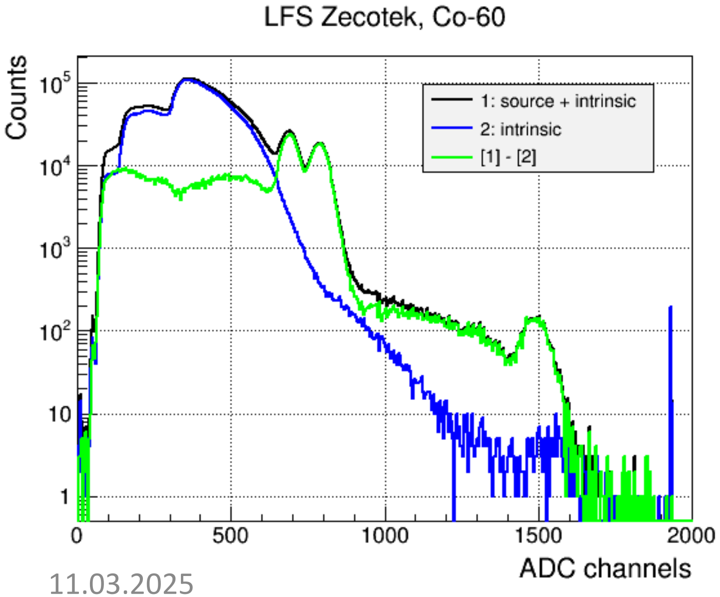
- All measurements were done with Hamamatsu PMT module H1949-50
- Crystals were attached to the PMT photocathode by means of optical grease
- Hamamatsu 5783 PMT with 1 cm^3 LGSO crystal was used for runs where coincidences with tested crystals required
- ^{22}Na, ^{137}Cs and ^{60}Co gamma sources were used for measurements of all crystals. One measurement of LFS crystal was done with ^{133}Ba source
- LeCroy ADC 2249W was used for signal processing. Signals from the PMT fed the ADC input with no additional amplification

Three LYSO crystals (2)

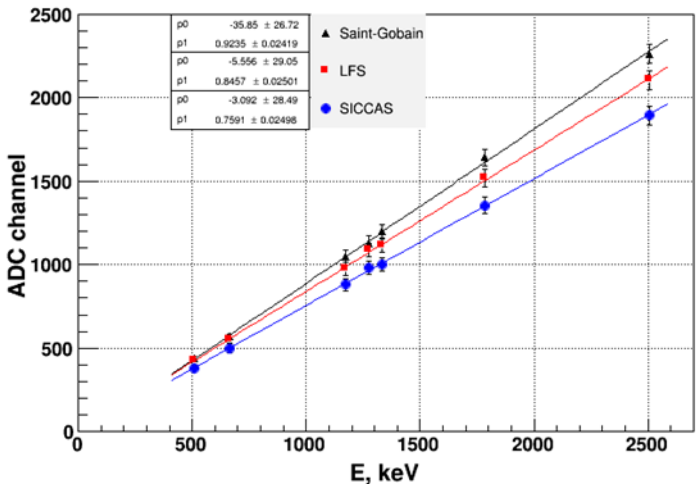


^{22}Na, self triggering





^{60}Co, self triggering

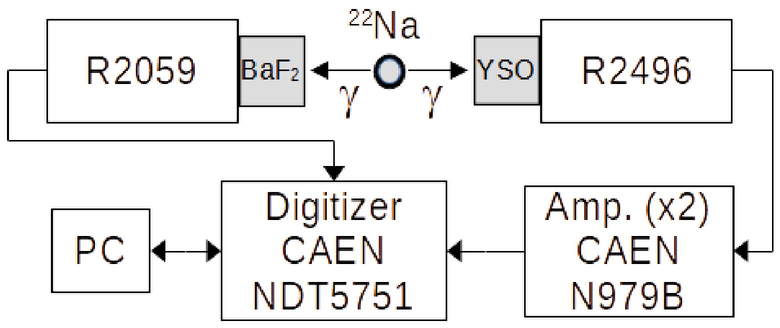


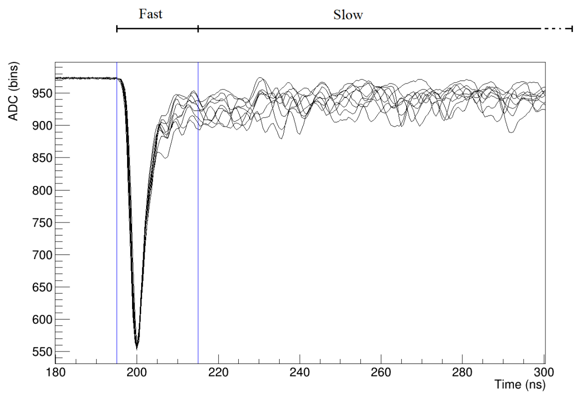
Irradiation of BaF_2 crystals

Four samples (1x1x1 cm^3) produced by SICCAS were selected: one pure BaF_2 crystal and three samples doped with yttrium in the proportions of 1 at.%Y, 3at.%Y and 5at.%Y

- All four samples were irradiated with neutron beam at IBR-2M reactor at JINR
- During the 14-day reactor cycle about 2.3×10^{14} n/cm^2 (E>1MeV) passed through the samples

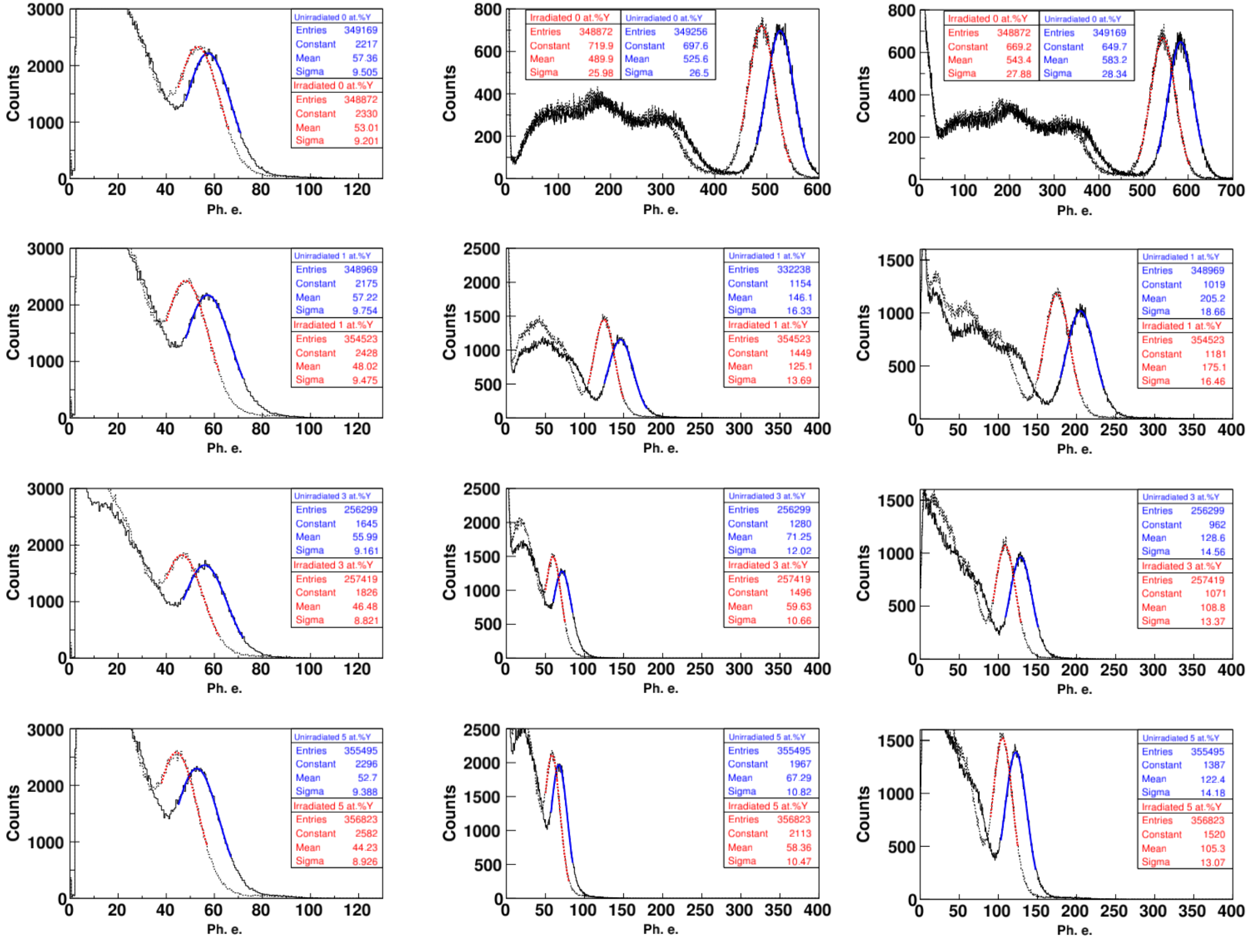
- All samples were measured before and after irradiation
- Light outputs were measured using ^{22}Na source
- Signals were digitized by CAEN NDT5751
- The total signal from the BaF_2 samples was measured for 2 µs, the fast component during the first 20 ns, and the slow component after 20 ns



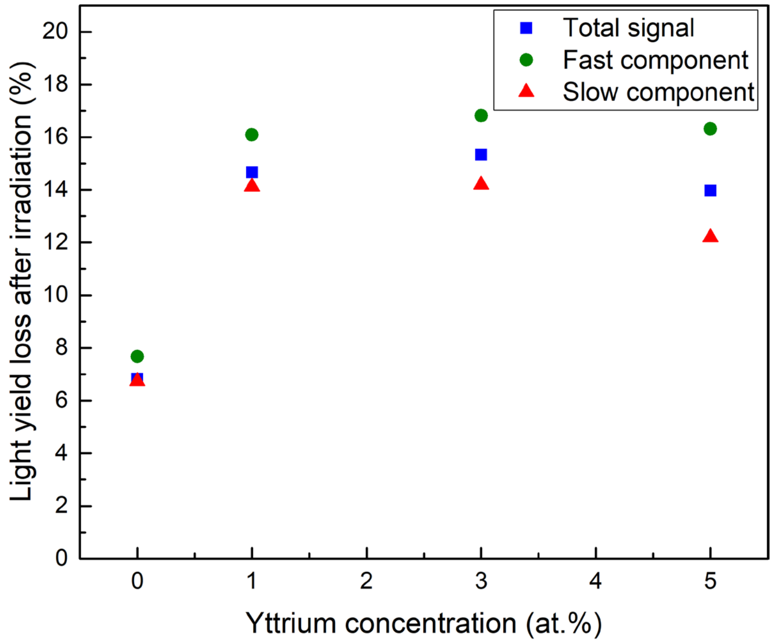


Spectra before and after irradiation

The light output was measured by the position of the total absorption peak of gamma rays with an energy of 511 keV



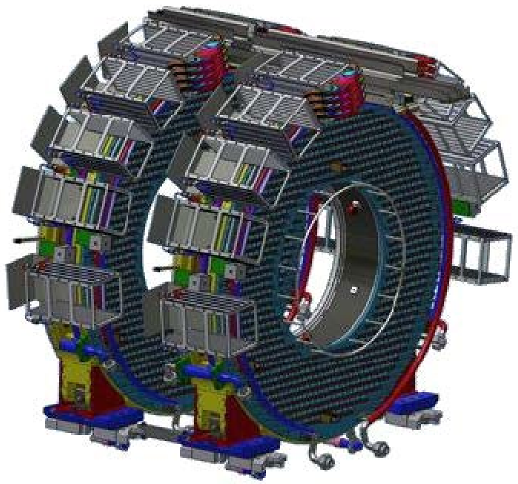
Fast Slow Total



- The light output loss of the pure BaF_2 crystal is about 7%.
- The light output loss of the yttrium doped samples is approximately two times higher than that of the pure BaF_2 sample.
- In all yttrium doped samples the light output loss of the fast emission component is 2-3% higher than that of the slow emission

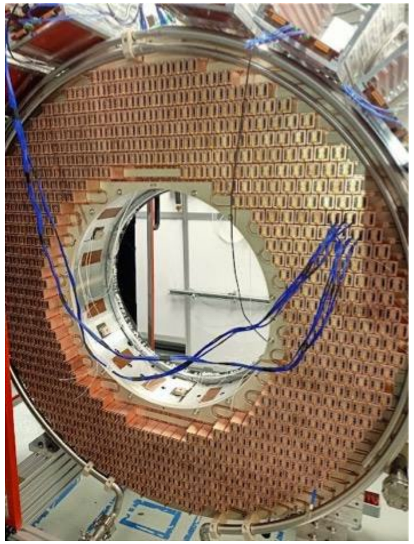
V. Baranov, Yu.I. Davydov, I.I. Vasilyev 2022 JINST 17 P01036

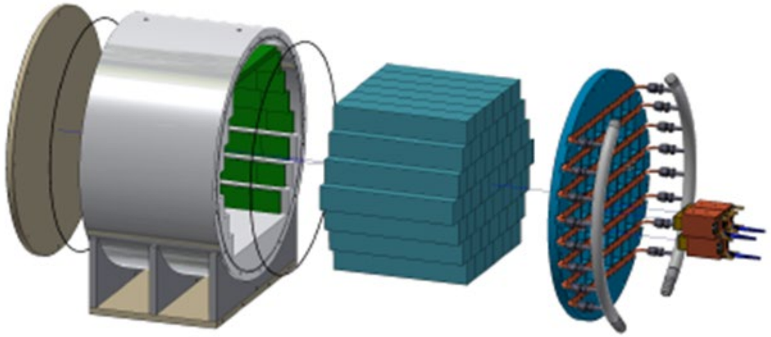
Prototypes of CsI crystal calorimeters



JINR along with LNF (Frascati, Italy) and Caltech (Pasadena, USA) participated in development of ECal

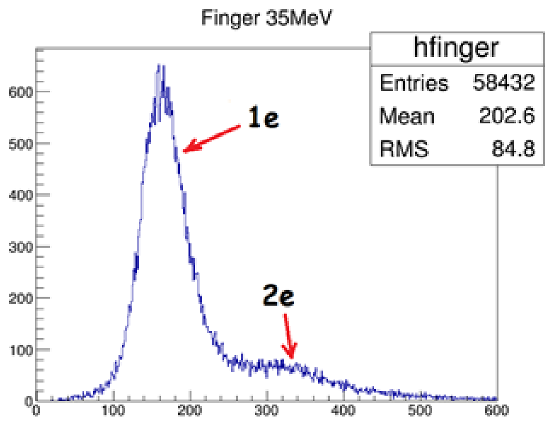
- The 5x5 LYSO array was tested in an electron beam at Frascati and a photon beam at Mainz
- 3x3 CsI arrays were tested in electron beams in Frascati and Yerevan (Armenia)
- Module-0 (51 crystals, 102 SiPMs, 102 FEE boards) with pre-productions and mechanics cooling systems similar to the final ones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

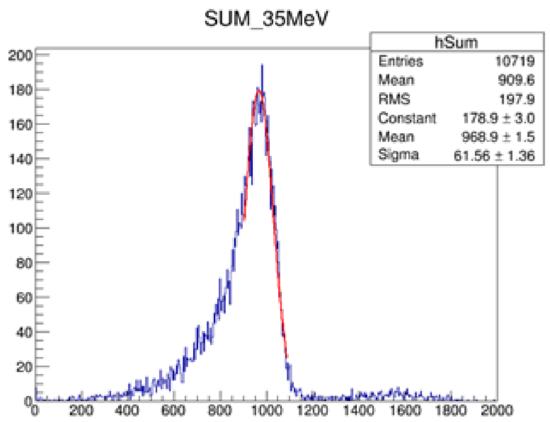


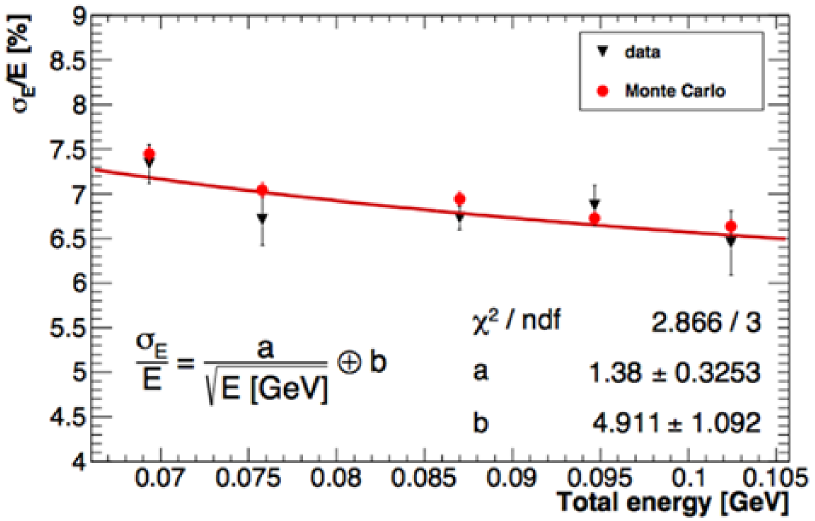


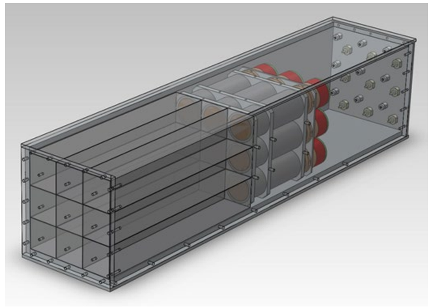
CsI: tests of 3x3 arrays in Frascati and Yerevan

- 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)



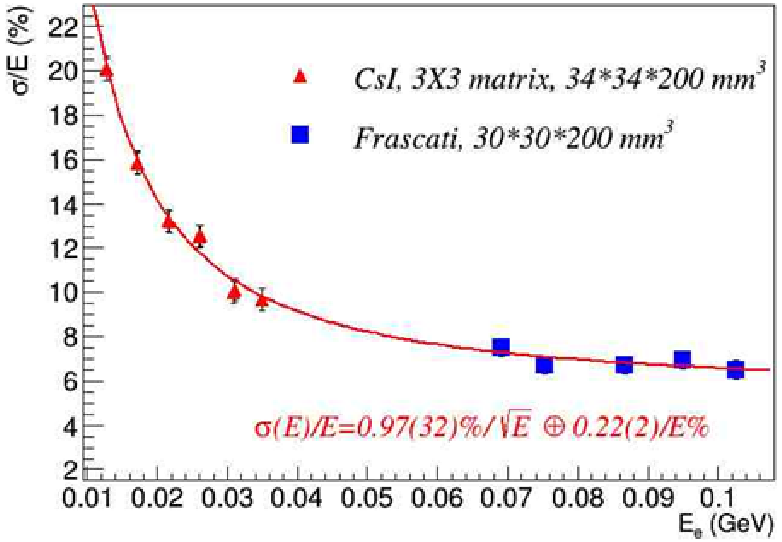




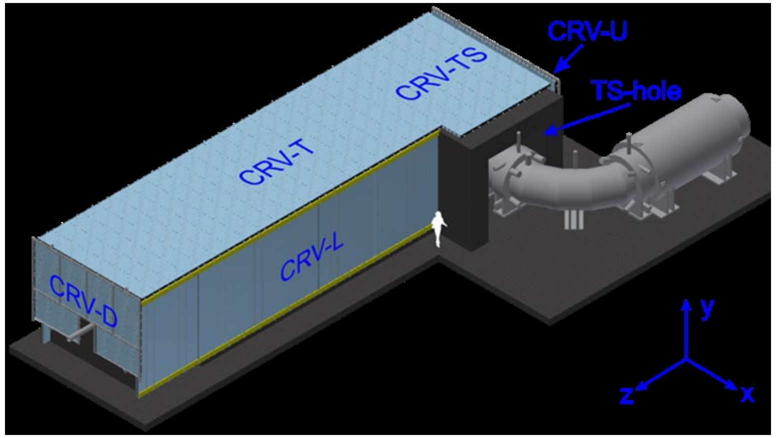


result from Frascati

Joint Frascati-Yerevan fit

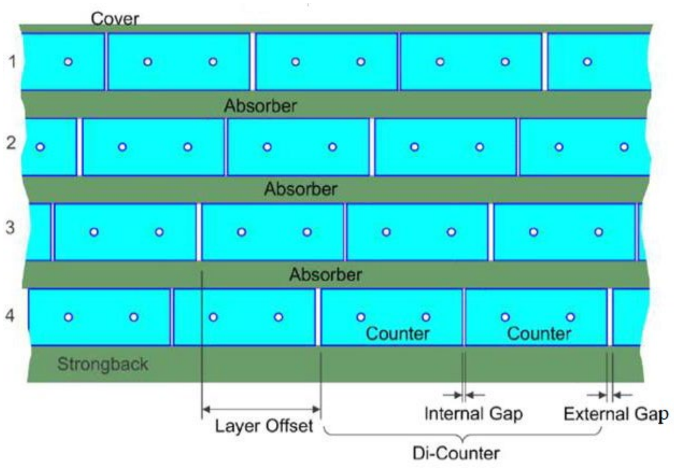


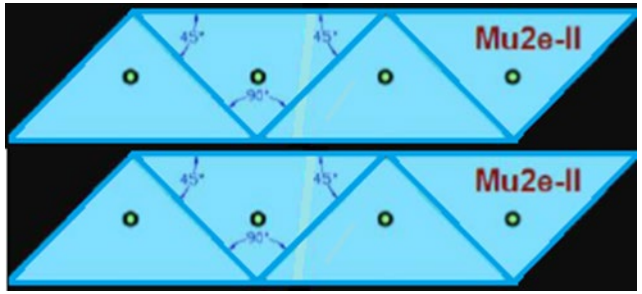
Mu2e CRV system



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 for mass production

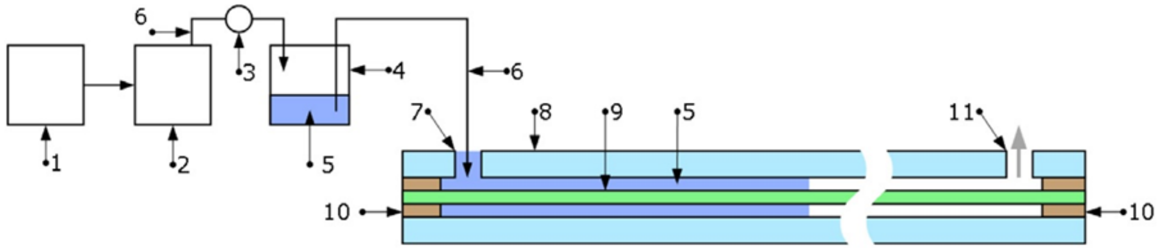


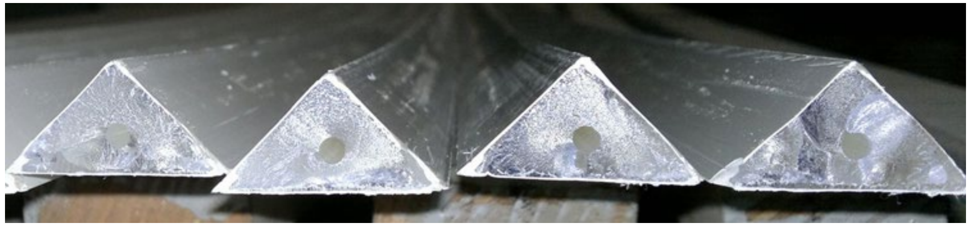


Tests of strips and CRV prototypes

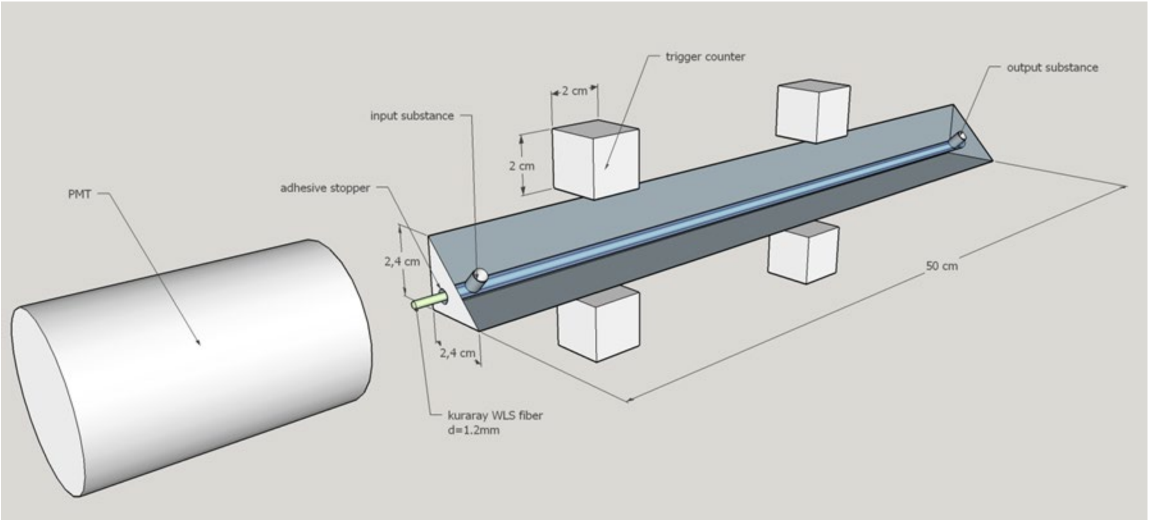
Tests of single strips, di-counters and CRV prototypes were carried out with cosmics rays and with beam at Fermilab

Light output increase with optical fillers

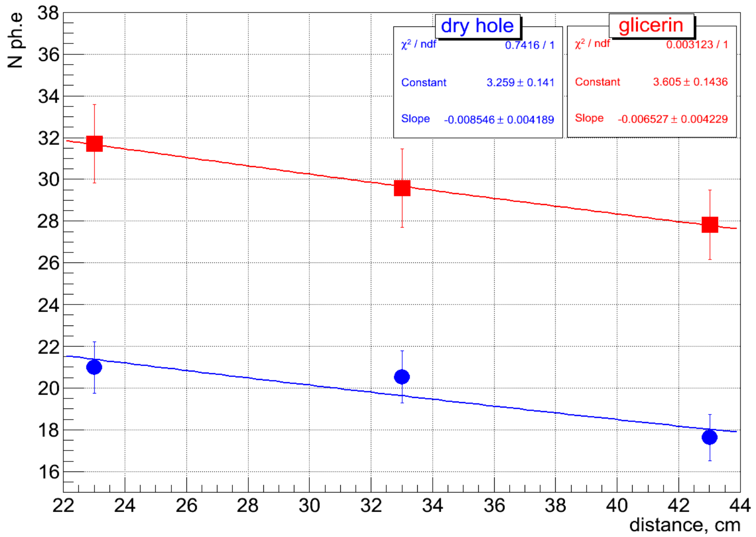


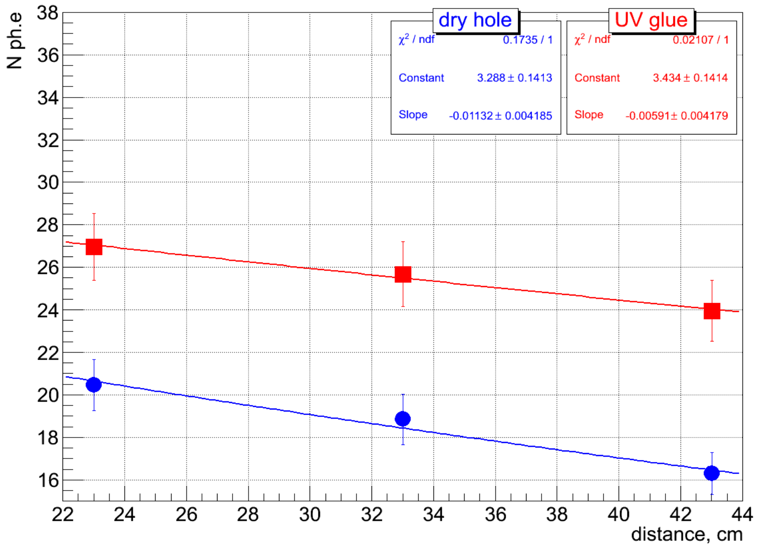


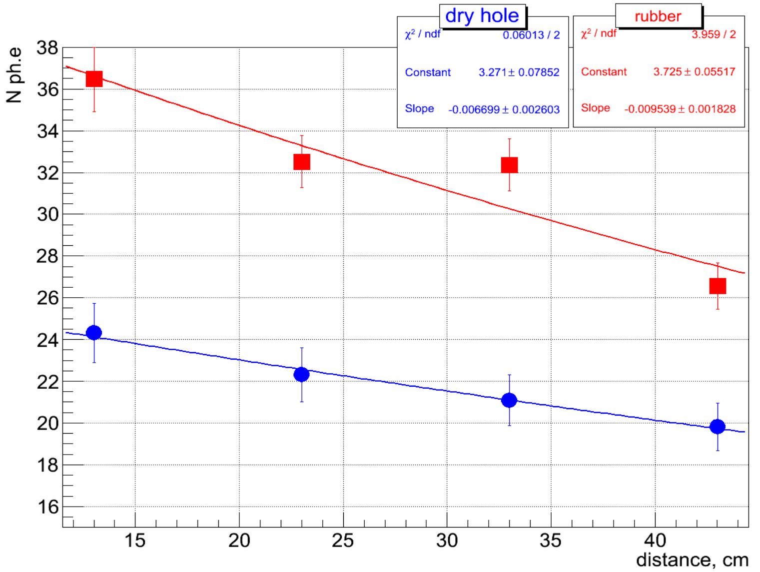
- A method has been developed for pumping optical fillers into holes with fibers inserted into them
- For the first tests, scintillators with a triangular cross-section were used
- Different liquid fillers were tested (distilled water, glicerin, viscous rubber CKTN-med, BC-600)
- Similar measurements were carried out by us at the University of Virginia with di-counters of the Mu2e muon system

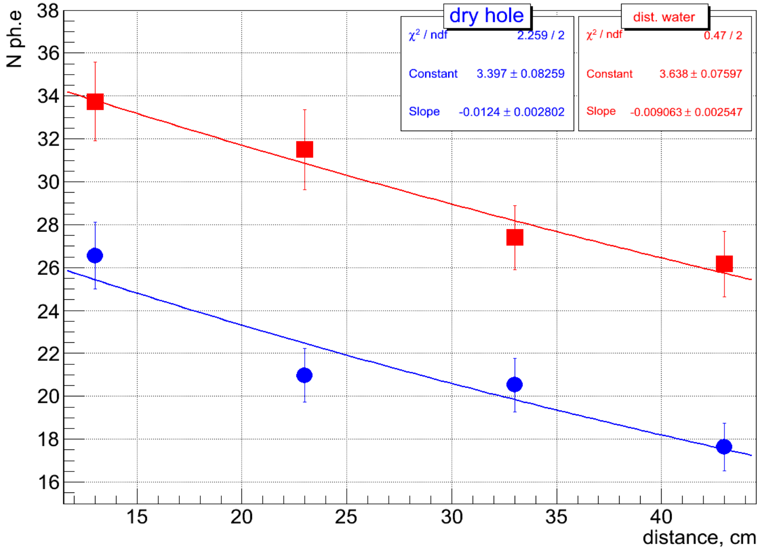


Light output increase with optical fillers (2)





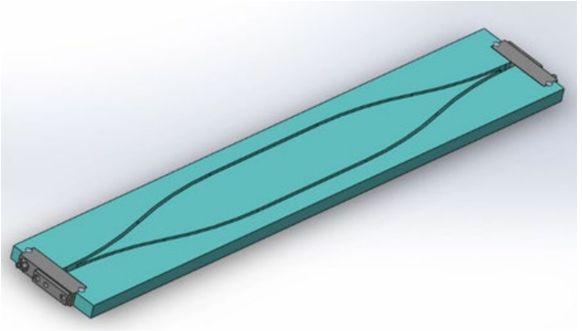




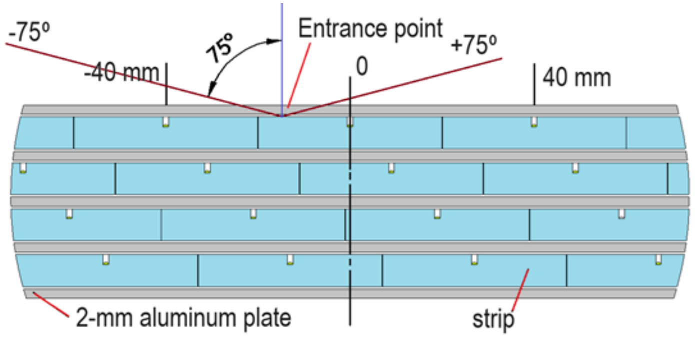
- Filling of the strip hole by the optical resin (CKTN-MED(E) or BC-600) gives the great increment of light yield by 1.4-1.5 times against to that of “dry” strip.
- Light yield study for the 5-m-long strip filled with SKTN-MED(E) carried out with cosmic muons and radioactive sources shows the same increase in the light yield

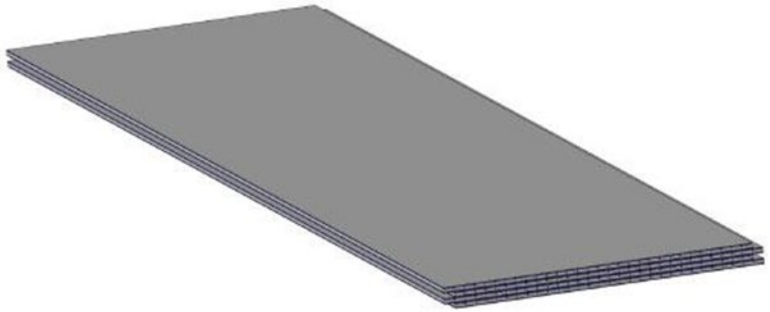
A.Artikov et al. *Optimization of light yield by injecting an optical filler into the co-extruded hole of the plastic scintillation bar. JINST 11(2016)T05003*
A.Artikov et al. *Light yield and radiation hardness studies of scintillator strips with a filler. NIM A930(2019)87-94*

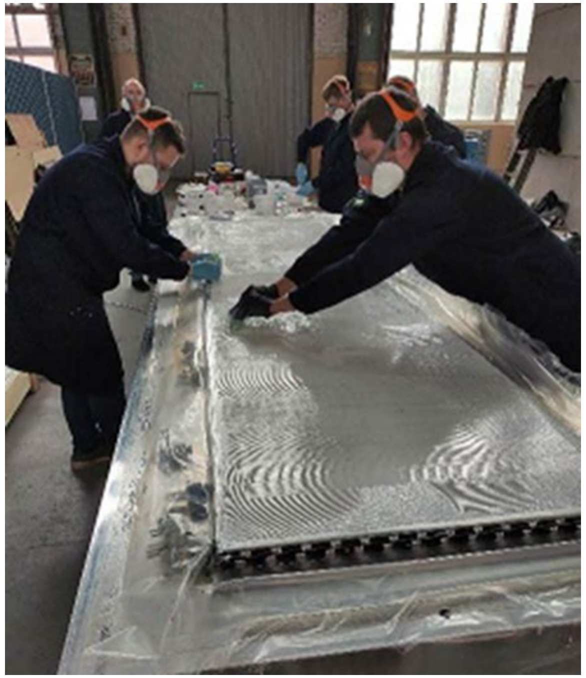
CRV module prototype with grooved strips



- Scintillators were extruded by company in Vladimir city (Russia)
- Diffuse reflective layer made by means a chemical etching
- Grooves for the WLS fibers were machined

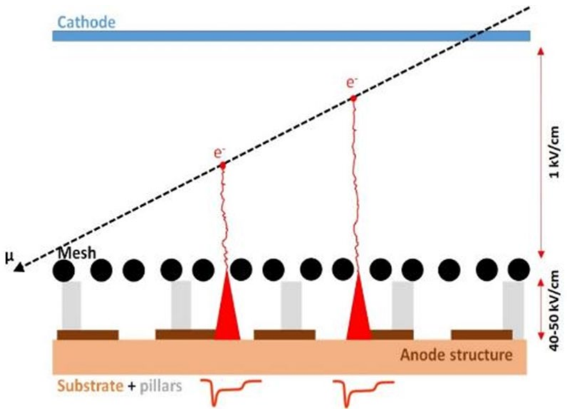




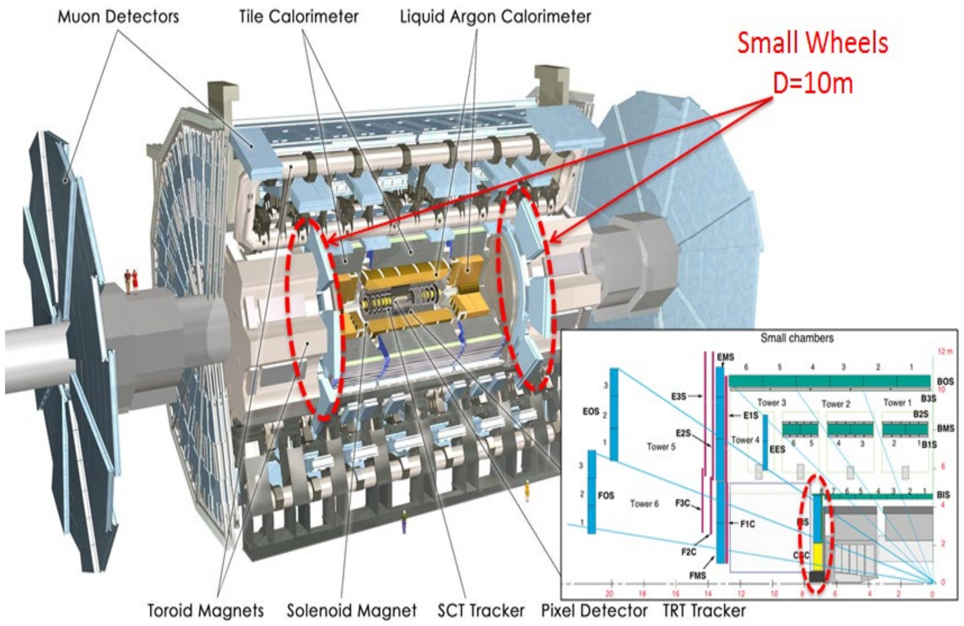


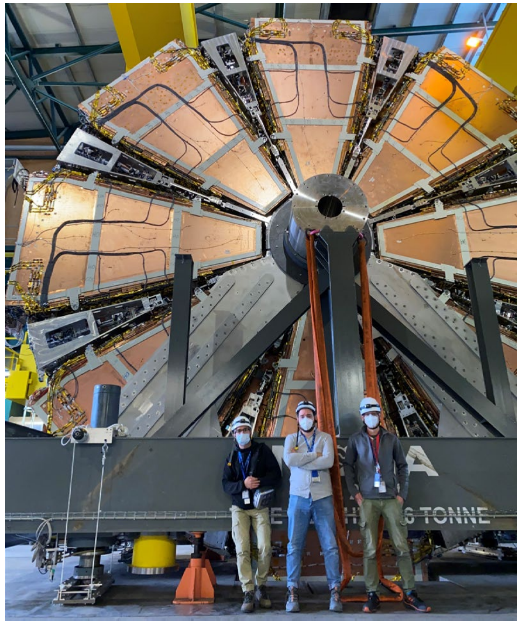
A.Artikov et al. *High efficiency muon registration system based on scintillator strips, NIM A1064(2024) 169436*

Micromegas production at JINR



- Two Micromegas detector production sites were constructed at the DLNP JINR.
- The first site was used for production and testing of Micromegas chambers for the outer part of the large sectors (LM2) of the New Small Wheels for the ATLAS Muon spectrometer.
- The second site is for a complete production cycle and intended for the R&D of Micromegas detectors with a width of up to 60 cm.

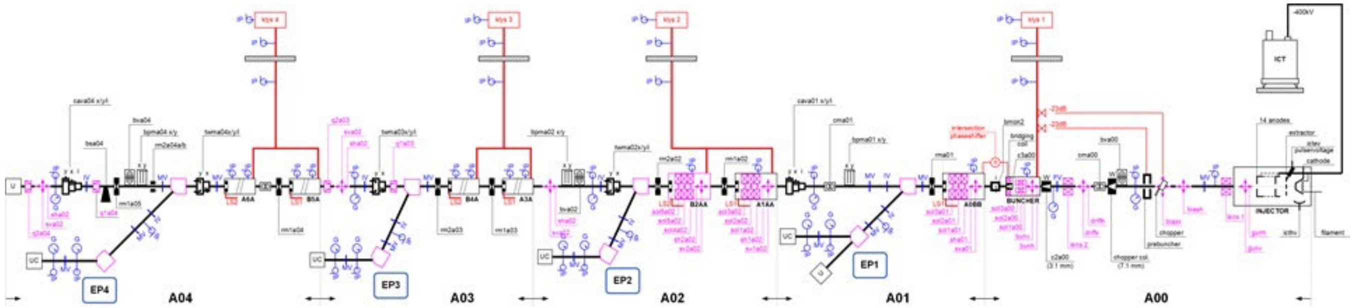




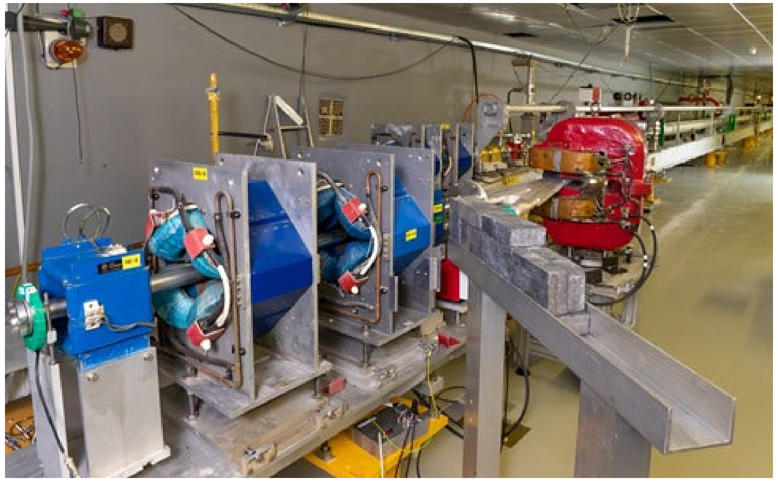
Facilities for R&D at JINR

- Linear electron accelerator LINAC-200
- Fast pulsed reactor IBR-2M
- Test beam at Nuclotron/NICA

Electron accelerator LINAC-200



- Each pulse consists of a sequence of bunches with a duration of 1 ps and an interval between bunches of 350 ps
- Intensity from 10^2 to 10^{13} e^-/s
- The transverse size of the extracted beam is ~1.5—5 mm
- Max. average current 5 μA
- Pulse duration 0.2-3.5 μs



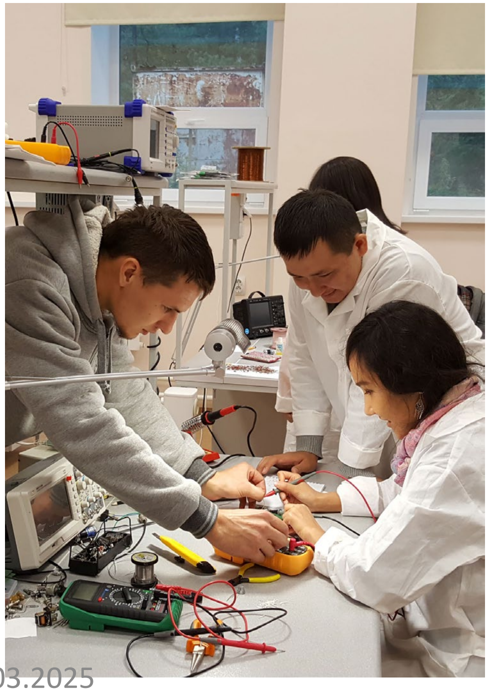
EP4

Two beam extraction points (EP1, EP4) are ready

	EP1	EP2	EP3	EP4
Electron energy, MeV	5-25	25-60	60-130	130-200
Pulse repetition rate, Hz	1-50	1-25		

Research program at the LINAC-200

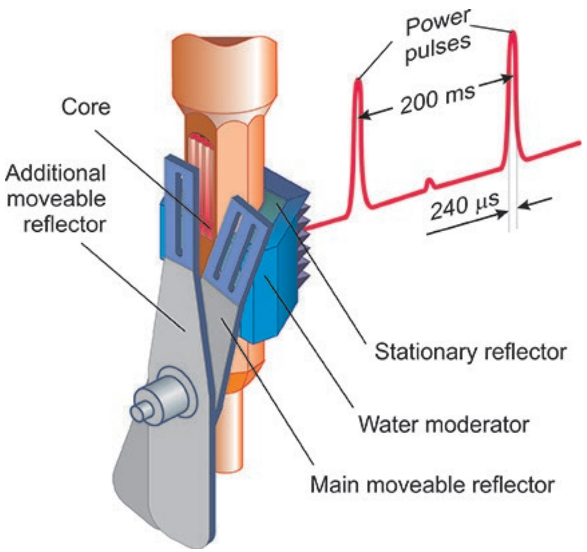
- Particle detectors R&D
- Terahertz radiation source and beam diagnostics R&D
- Applied research
- Nuclear physics experiments
- Education and training



Future prospect:

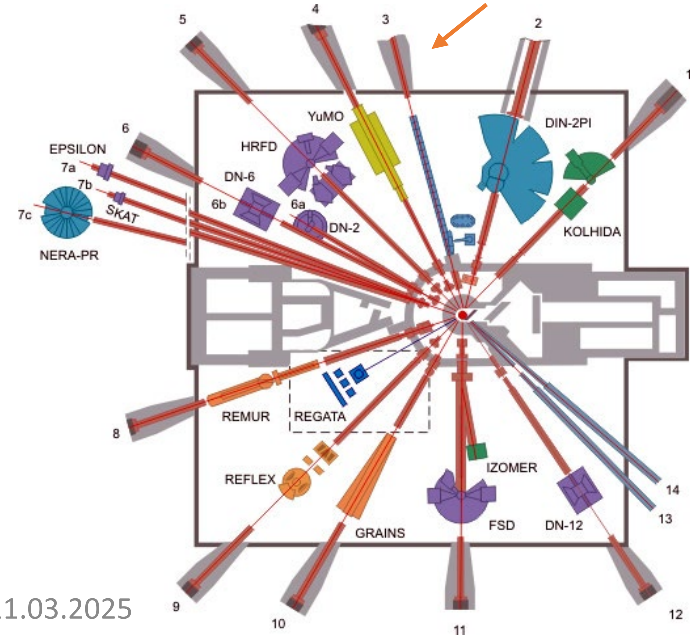
- Increasing the accelerator energy up to **400 MeV** – commissioning of accelerator stations 4 and 5 – 2026.
- In the future, it is possible to increase the energy up to **800 MeV**

Research reactor IBR-2M at JINR



- IBR-2 at Frank Laboratory of Neutron Physics, JINR is a pulsed fast reactor of periodic operation. Its main difference from other reactors consists in mechanical reactivity modulation by a movable reflector.
- 14 channels have been created for experiments with neutrons in a wide range of energies, from ultracold to fast.
- A special irradiation facility was created on channel No. 3

Ch.#3

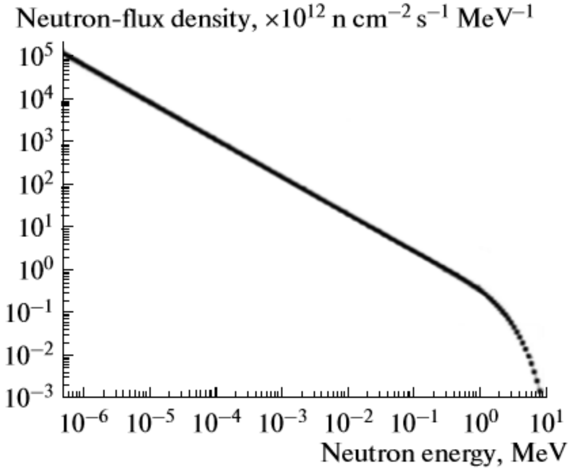


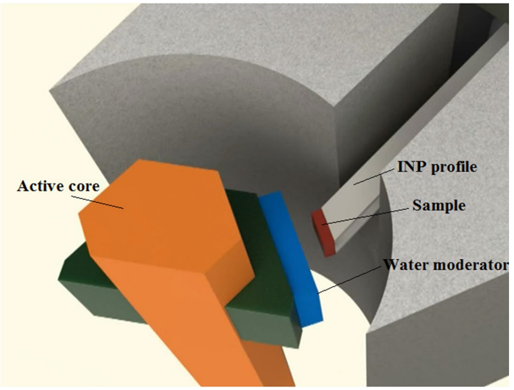
Average power, MW	2
Fuel	PuO_2
Number of fuel assemblies	69
Pulse repetition rate, Hz	5; 10
Pulse half-width, µs:	240
Rotation rate, rev/min:	
main reflector	600
auxiliary reflector	300
Thermal neutron flux density from the surface of the moderator:	
- time average	10^{12} - 10^{13} n/cm²·s
- burst maximum	~ 10^{16} n/cm²·s

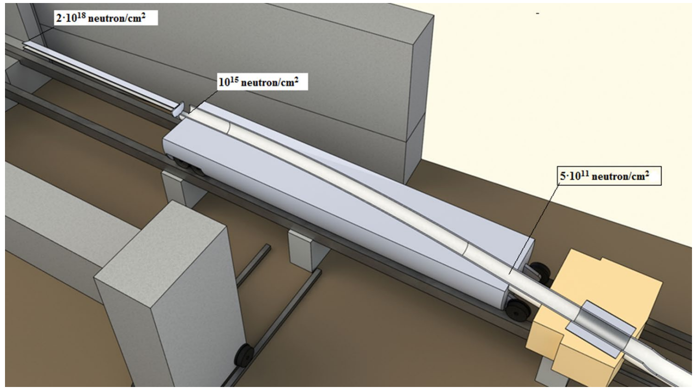
https://flnp.jinr.int/en-us/main/facilities/ibr-2

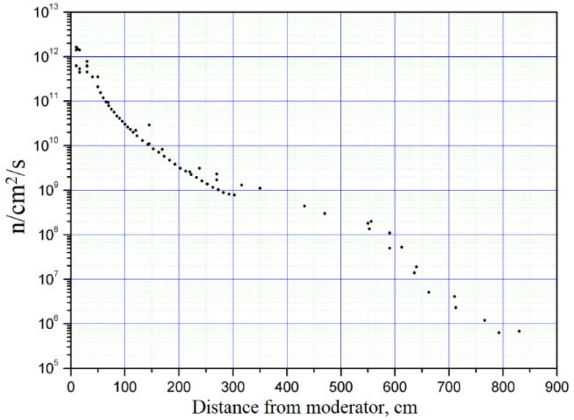
Irradiation channel #3 at IBR-2M

- Irradiating samples could be placed inside of the pipe or on the I-beam. In the running position the I-beam end is located within a few centimeters from the water moderator
- During the two weeks running cycle fluence is ~10^{18} n/cm^2 on the I-beam end and 10^{16} n/cm^2 and 10^{11} n/cm^2 at the beginning and end of the pipe respectively









The neutron flux decreases with distance from the water moderator

Summary

- The JINR group has extensive experience in participating in leading experiments in elementary particle physics
- Members of the group played leading roles in the design and construction of large experimental setups in several experiments
- The group members carry out a large volume of research work on the development and study of new detectors. The existing infrastructure of JINR expands the possibilities of such research
- We believe that our experience of participating in leading world experiments will enable us to make a significant contribution to the preparation and implementation of experiments at CEPC