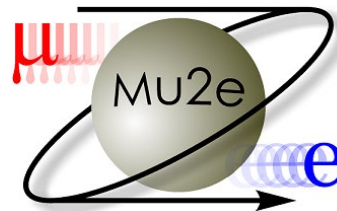
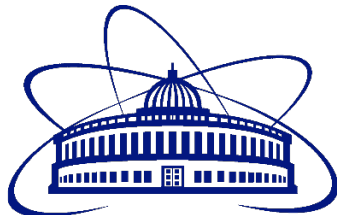


Irradiation of BaF₂ samples: some results and immediate plans

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on behalf of the JINR, Dubna group

*Workshop on a Future Muon Program at Fermilab
Caltech, March 27-29, 2023*



Outline

- Motivation
- Irradiation at IBR-2M reactor at JINR
- Results of neutron irradiation
- Plans for electron irradiation at the Linac-200 accelerator at JINR
- Simulation of energy losses in crystal samples in an electron beam

Motivation

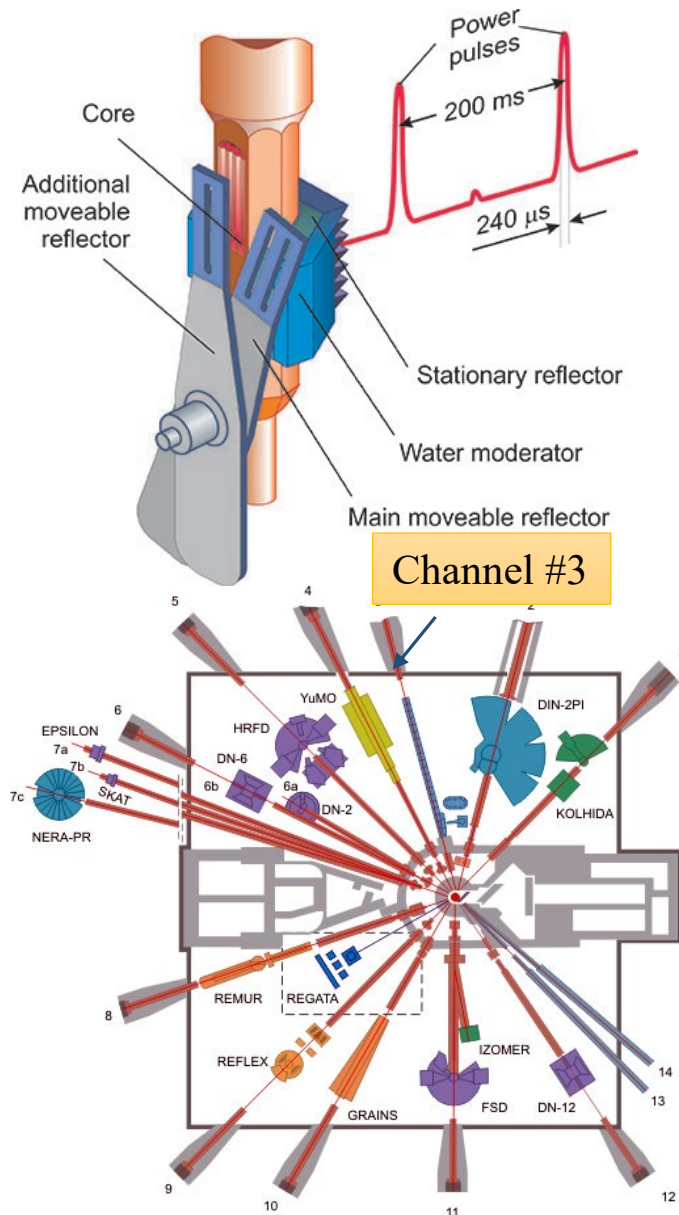
Motivation: possible use of pure BaF_2 / Y doped BaF_2 / LYSO crystals in the Mu2e-II electromagnetic calorimeter

We have sets of pure and Y-doped BaF_2 crystal samples from both BGRI and SICCAS (China):

1. BaF_2 pure crystal, 10x10x10 mm
2. BaF_2 crystal doped with Y (1at.%Y), 10x10x10 mm
3. BaF_2 crystal doped with Y (3at.%Y), 10x10x10 mm
4. BaF_2 crystal doped with Y (5at.%Y), 10x10x10 mm

We also expect to receive LYSO samples from SICCAS soon

IBR-2M reactor at JINR



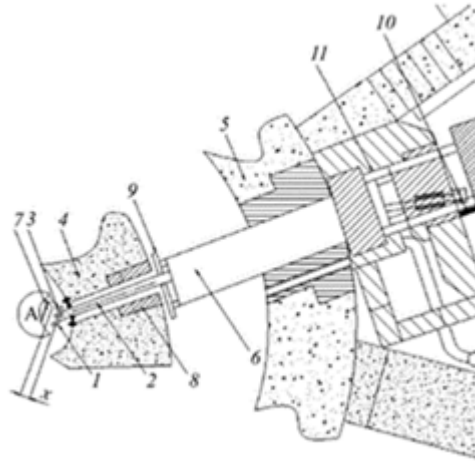
- IBR-2 at Frank Laboratory of Neutron Physics, JINR is a pulsed fast reactor of periodic operation. Its main difference from other reactors consists in mechanical reactivity modulation by a movable reflector.
- 14 channels have been created for experiments with neutrons in a wide range of energies,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

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	$10^{12} - 10^{13} \text{ n/cm}^2 \cdot \text{s}$
- burst maximum	$\sim 10^{16} \text{ n/cm}^2 \cdot \text{s}$

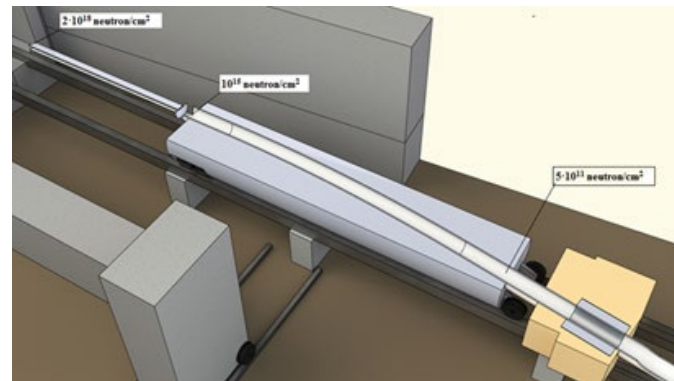
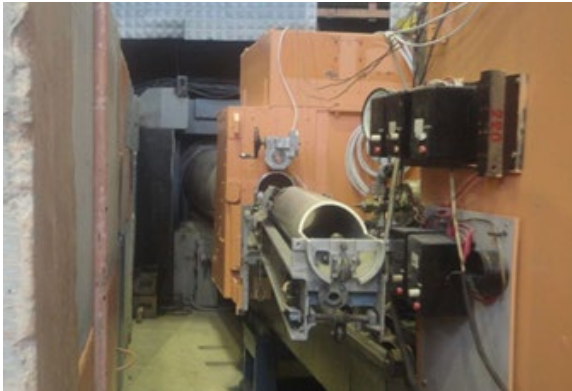
<http://flnph.jinr.ru/en/facilities/ibr-2/parameters>

Neutron irradiation channel

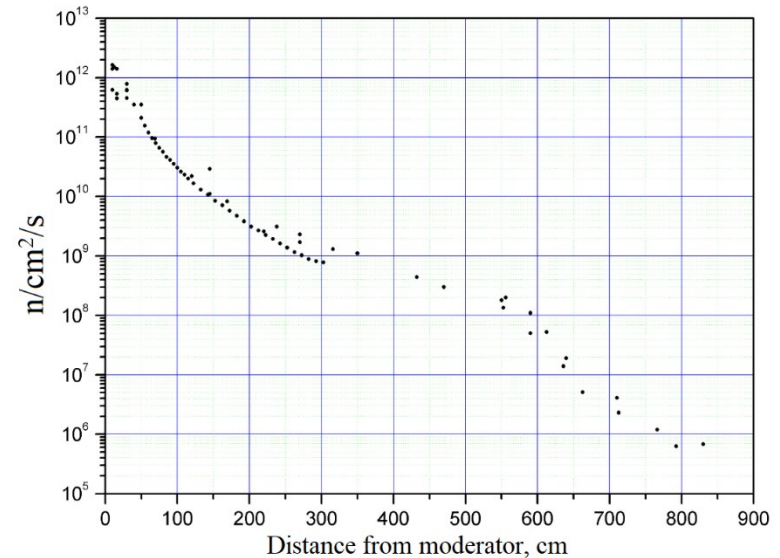
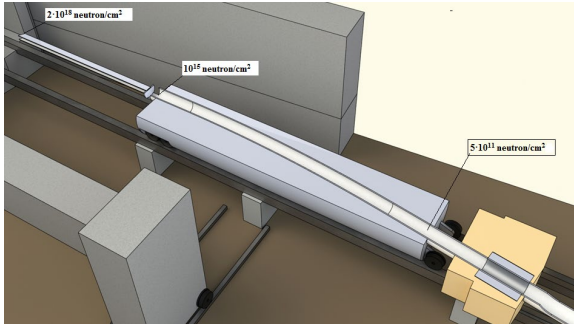
Irradiating samples could be placed inside of the pipe or on the I-beam. In the running position the I-beam end is located within a few centimeters from the water moderator



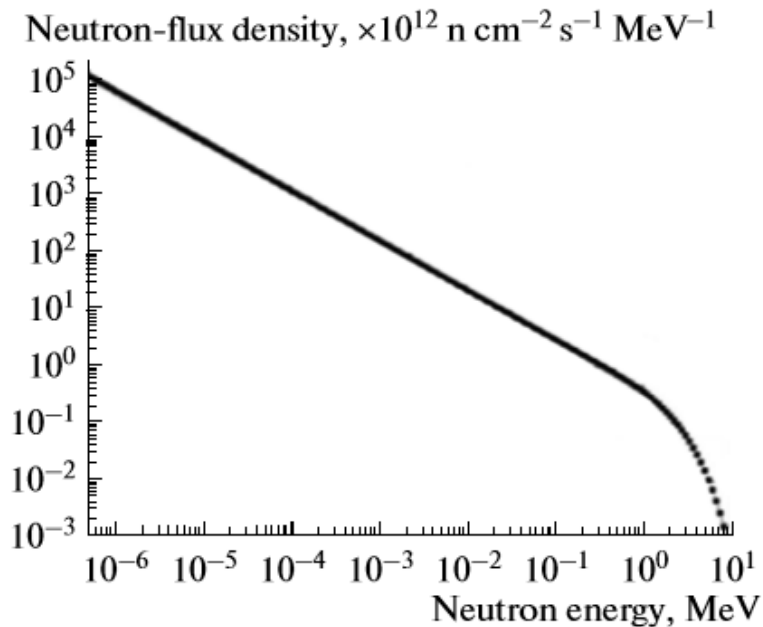
During the two weeks running cycle fluence is $\sim 10^{18}$ n/cm² on the I-beam end and 10^{16} n/cm² and 10^{11} n/cm² at the beginning and end of the pipe respectively



Neutron flux and spectrum



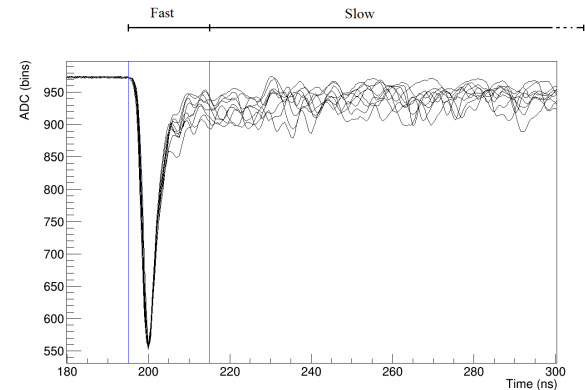
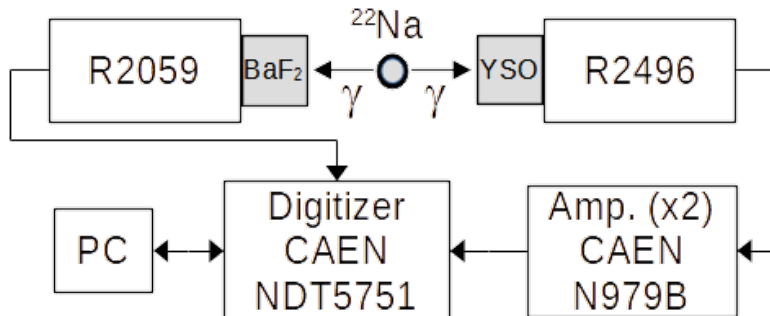
The neutron flux decreases with distance from the water moderator



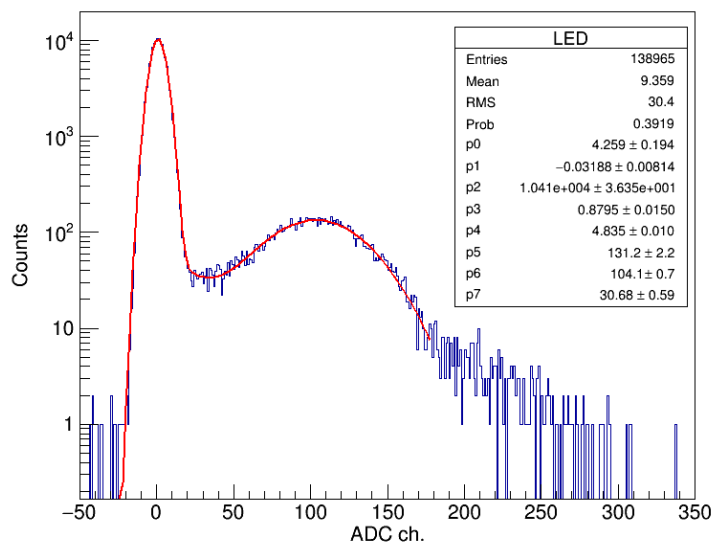
Irradiation of samples

For the first session of neutron irradiation, only four samples ($1 \times 1 \times 1 \text{ cm}^3$) produced by SICCAS were selected: one pure BaF_2 crystal and three samples doped with yttrium in the proportion of 1 at.%Y, 3at.%Y and 5at.%Y

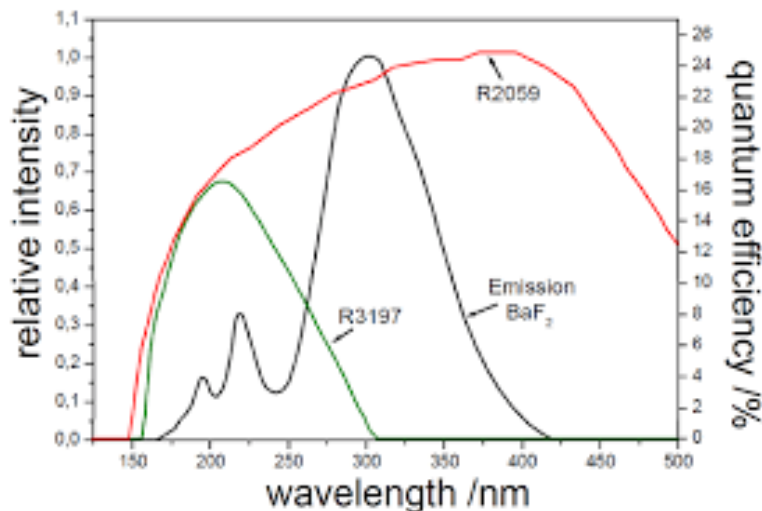
- All four samples were placed together about 5 m from the water moderator
 - During the 14-day reactor cycle about $2.3 \times 10^{14} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) passed through the samples
- All samples were measured before and after irradiation
 - Light outputs were measured using ^{22}Na source
 - Signals were digitized by CAEN NDT5751
 - The total signal from the BaF_2 samples was measured for $2 \mu\text{s}$, the fast component during the first 20 ns, and the slow component after 20 ns



R2059: calibration and QE



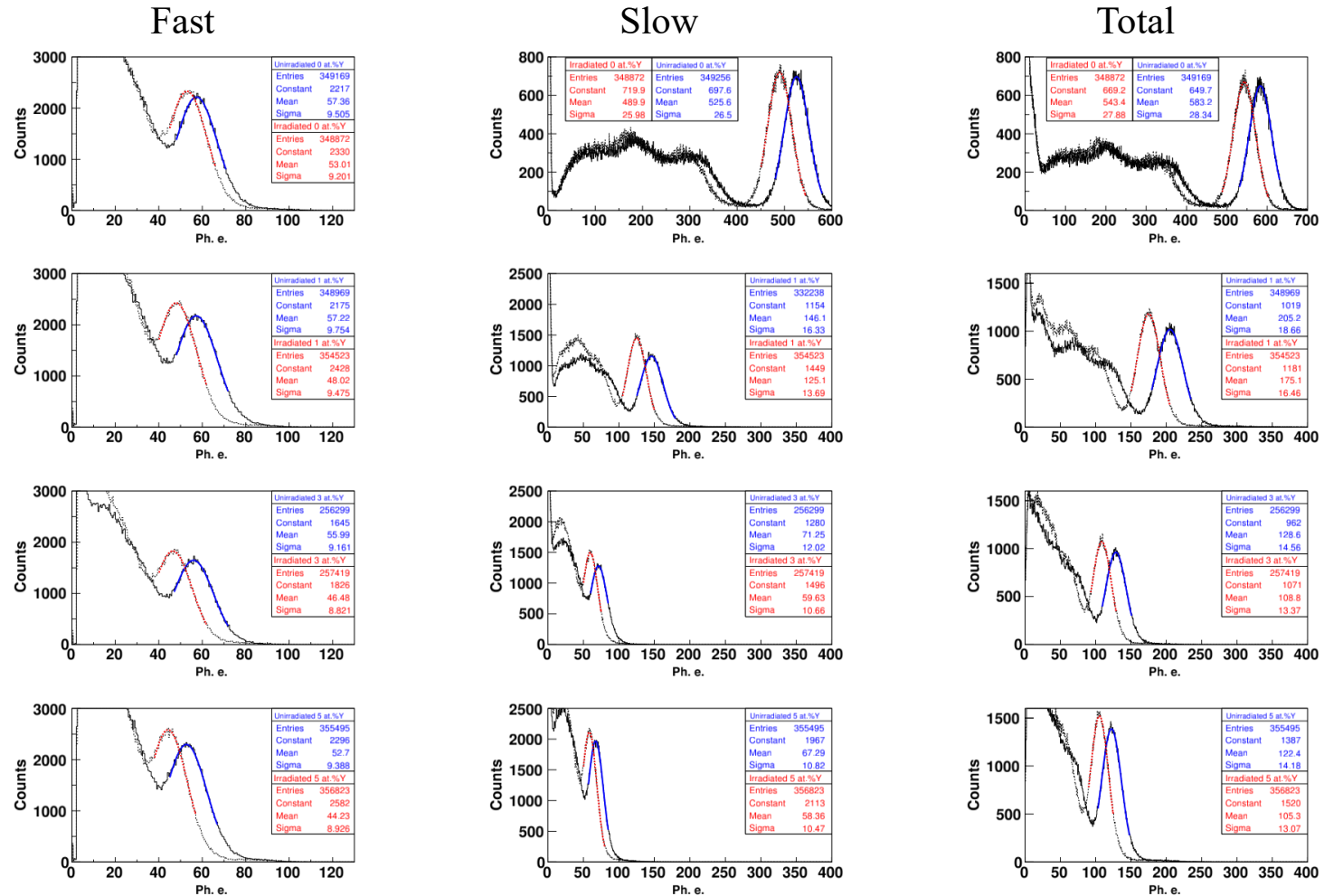
The measuring channel was calibrated using a single electron peak by illuminating the PMT photocathode with low-intensity light. The spectrum was fitted with an exponential function describing the noise and two Gaussians describing the pedestal and single electron events. Most of the events in the spectrum fall into the pedestal. The average number of photoelectrons in the spectrum is $\mu \approx 0.086$



The R2059 PMT has a quantum efficiency of about 16-17% in the fast luminescence region (200-220~nm) and about 23-24% in the slow luminescence region (310~nm). The measured light outputs of the fast and slow luminescence of the samples were not corrected for the difference in the quantum efficiency of the PMT

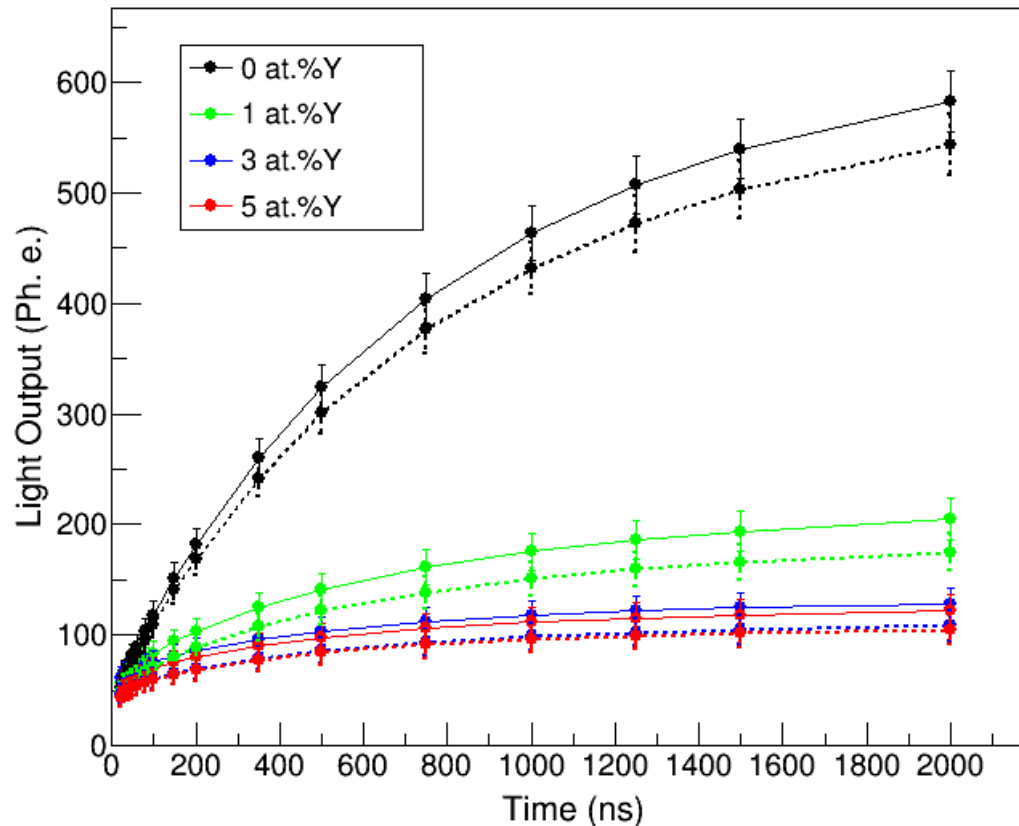
Spectra before and after irradiation

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

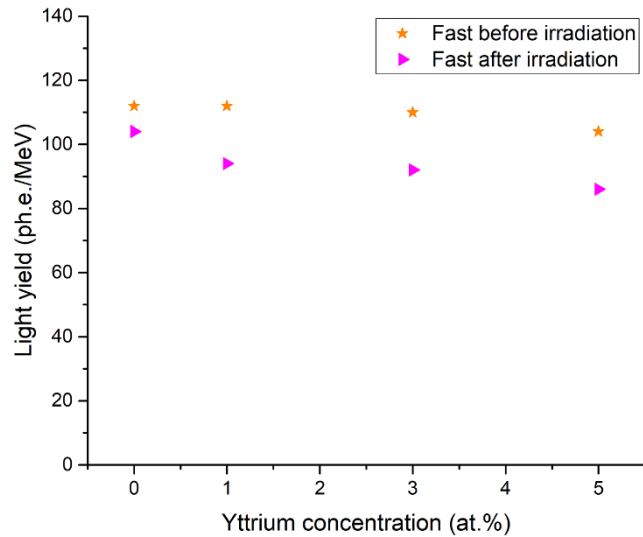


Light output versus time

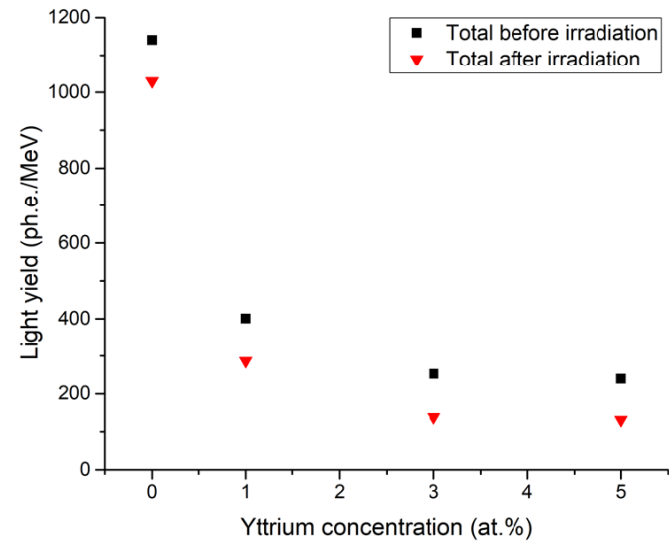
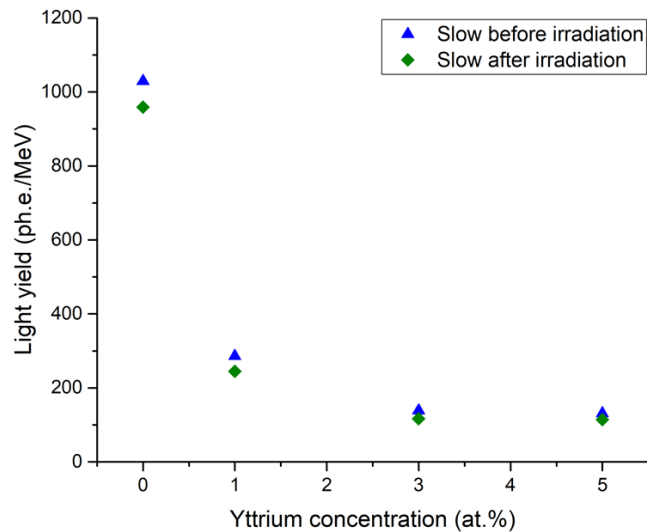
Light outputs of the pure and yttrium doped BaF_2 samples before (solid lines) and after (dashed lines) irradiation as a function of the integration time



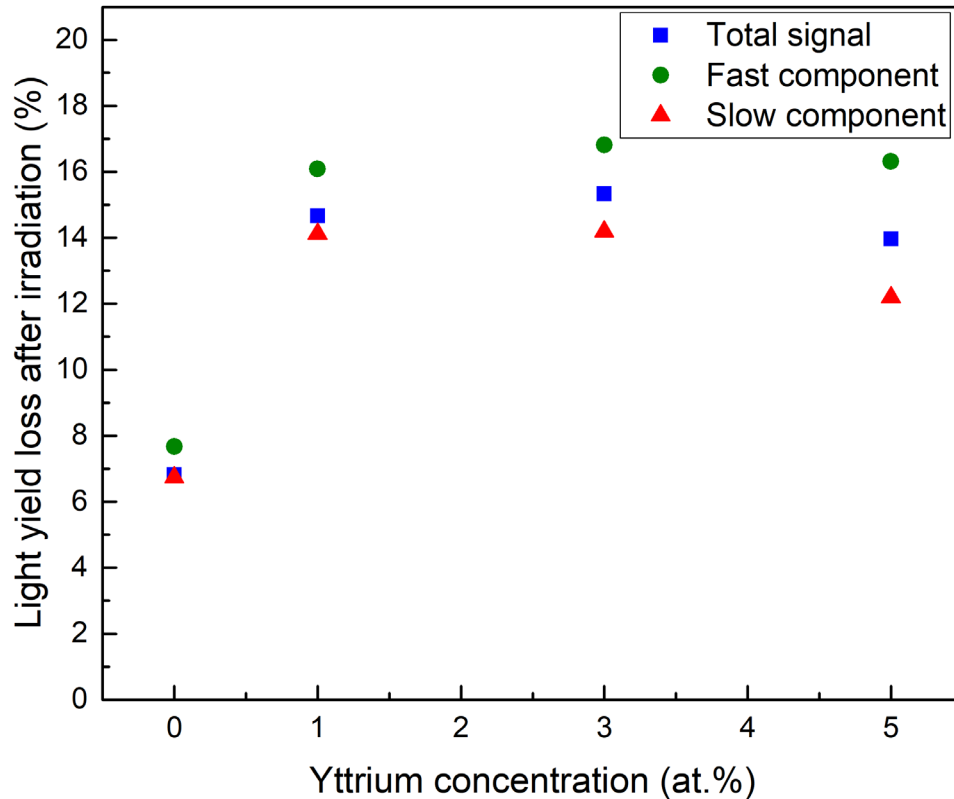
Light outputs before and after irradiation



Pure BaF₂ has lower light output loss compared to Y-doped samples



Light yield loss after irradiation



- 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

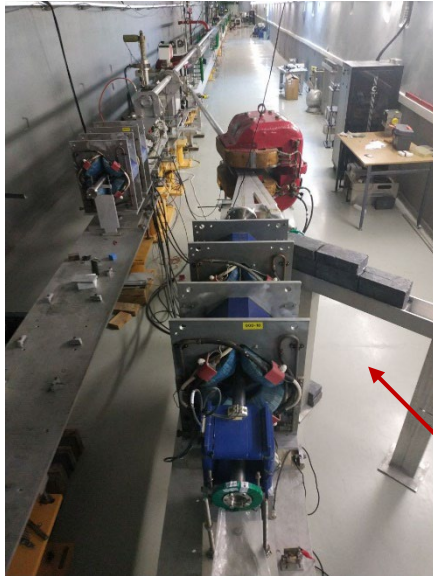
More studies required!

Electron beam irradiation

We plan to irradiate samples with an electron beam at Linac-200 at JINR

It is required to optimize the beam size, irradiation time, etc.

Linac-200 at JINR

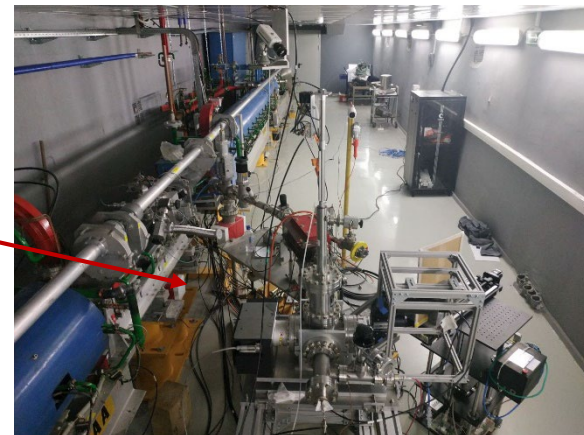


- Linac-200 is a linear electron accelerator created at Dzhelepov Laboratory of Nuclear Problems, JINR
- Currently Linac-200 has two beam extraction lines for 5-25 MeV and 40-200 MeV
- Linac-200 parameters: beam frequency from 1 to 25 Hz; beam intensity – from tens of electrons/second to 80 mA in a pulse with a duration of 0.25-3.0 μ s
- The commissioning of the Linac-200 is expected to be completed in a few months

*40-200 MeV
extraction line*



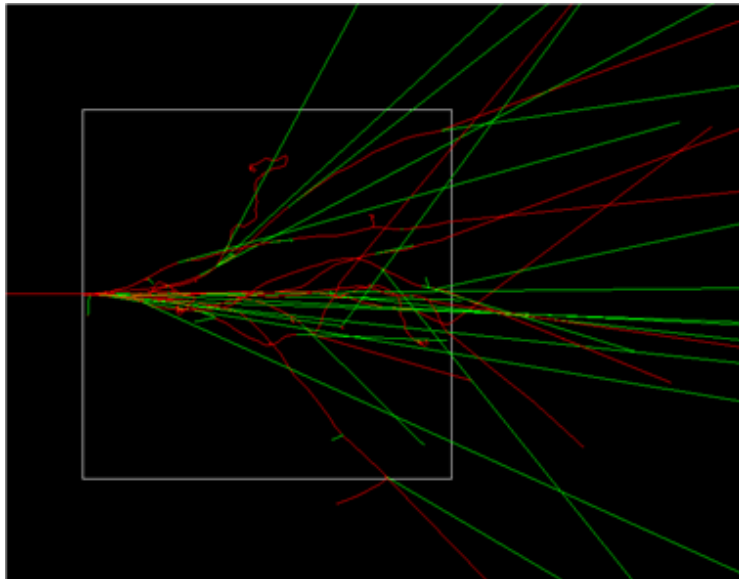
*5-25 MeV
extraction line*



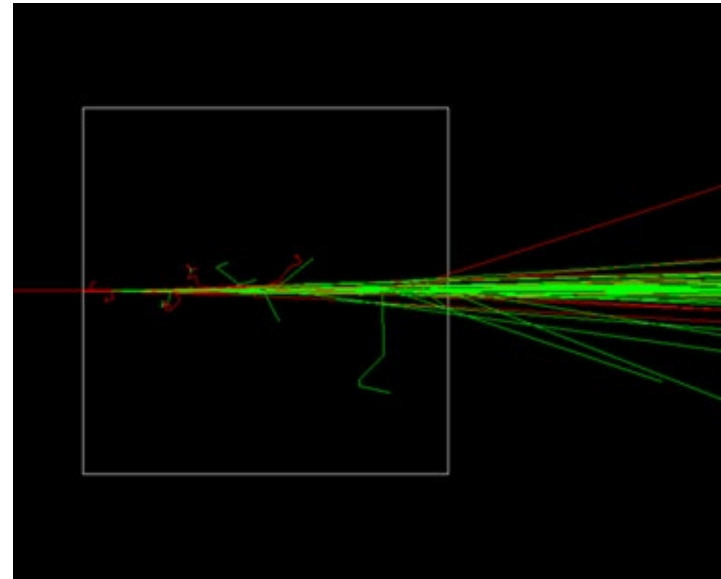
Simulation of energy losses in crystal samples

Showers in cubes under electron irradiation

20 MeV



200 MeV

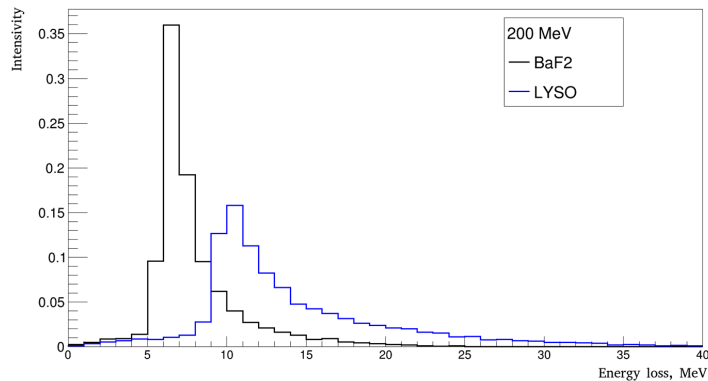
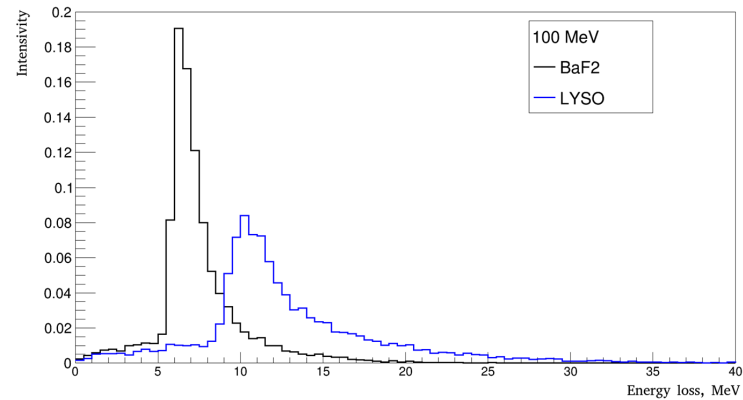
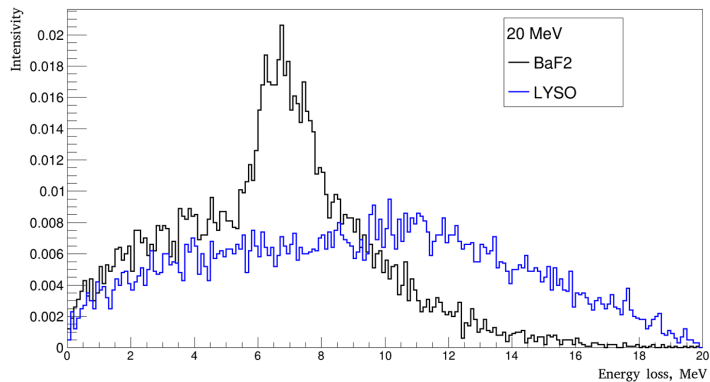


Red: electrons

Green: gammas

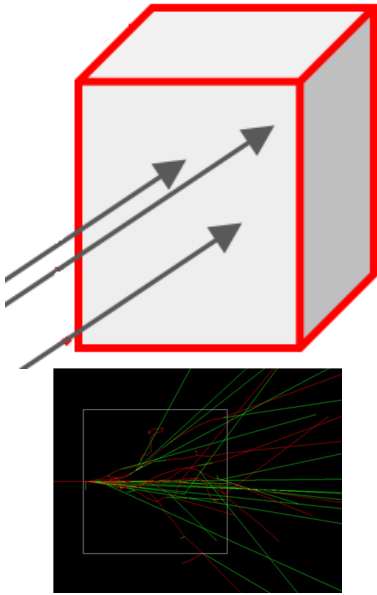
Energy losses in a 1 cm³ BaF₂ cube

The electron beam is uniformly distributed over the face of the cube



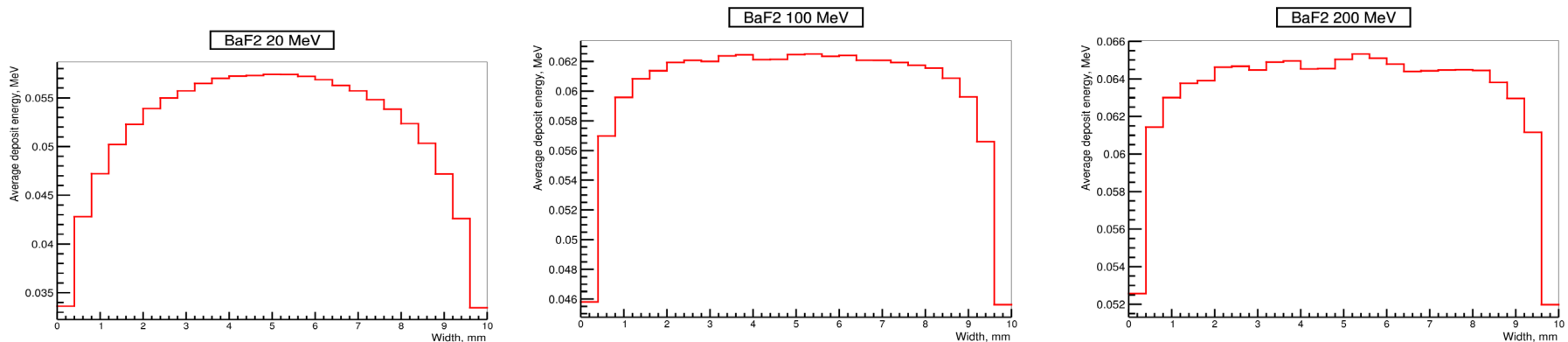
	BaF ₂	
	Mean	RMS
20 MeV	6.45	3.12
100 MeV	7.46	2.73
200 MeV	7.92	2.96

Transverse distribution of deposited energy

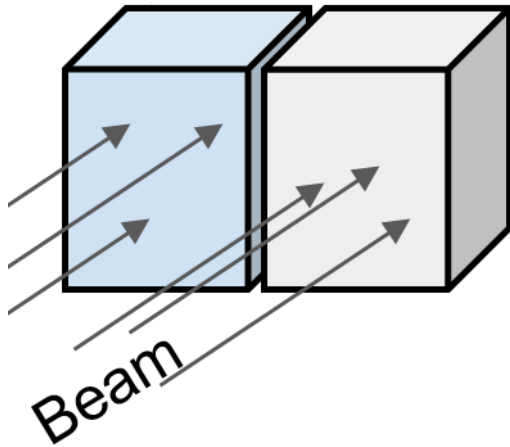


- The electron beam is uniformly distributed over the face of the cube
- Cube “divided” on 25 vertical slices along of a beam direction
- At $E=20$ MeV, there is a noticeable drop in deposited energy at the edges, which is explained by energy leakage through the side faces

The data are normalized to the total number of electrons falling on 5 cubes (the test cube and 4 neighboring ones). Only every fifth electron leaves energy in the tested cube

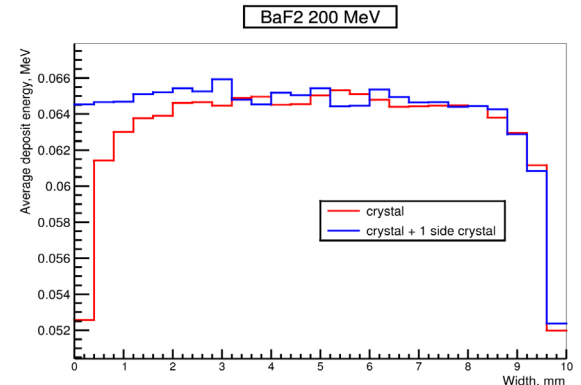
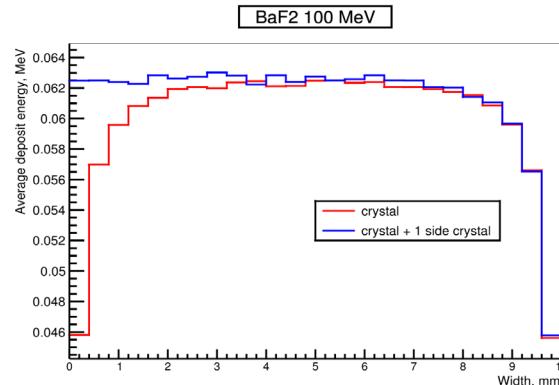
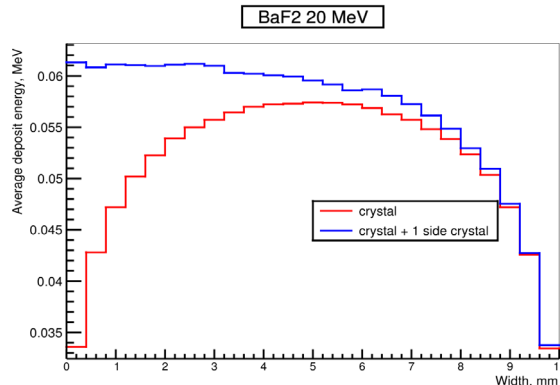


Transverse distribution of deposited energy with an adjacent cube

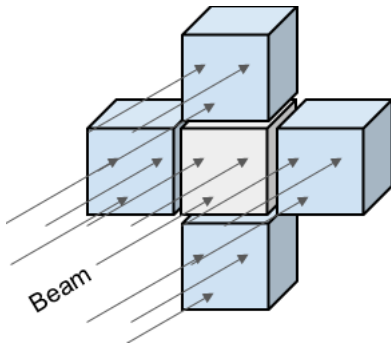


- Placing an adjacent cube helps improve the uniformity of energy loss in the cube
- The electron beam is uniformly distributed over the faces of both cubes
- The leakage of energy from the main cube is compensated by the leakage of energy from the neighboring cube

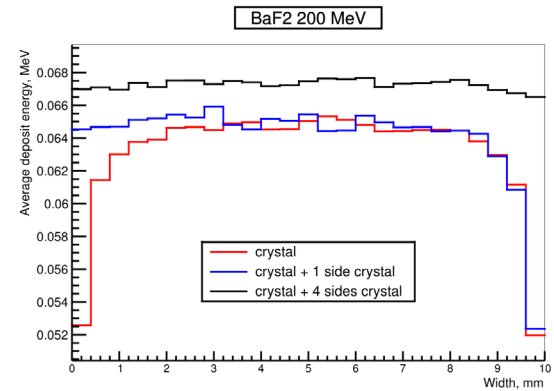
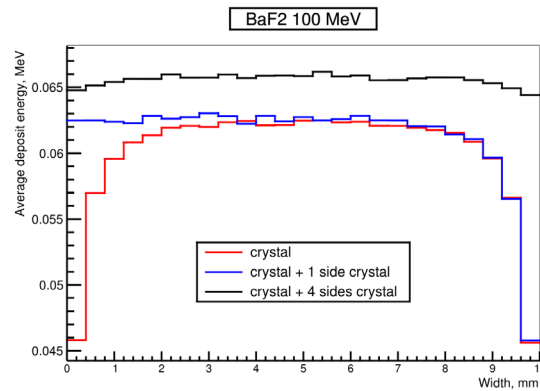
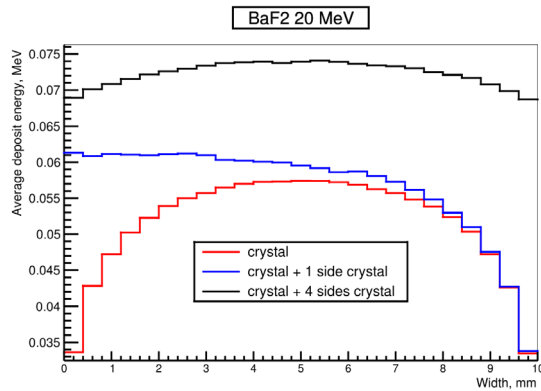
Again, the data are normalized to the total number of electrons falling on 5 cubes. Only every fifth electron leaves energy in the tested cube



Transverse distribution of deposited energy with 4 adjacent cubes

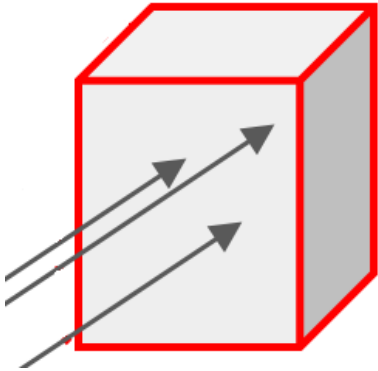


- 4 neighboring cubes can improve the uniformity of irradiation
- However, this requires the use of a very wide uniform beam

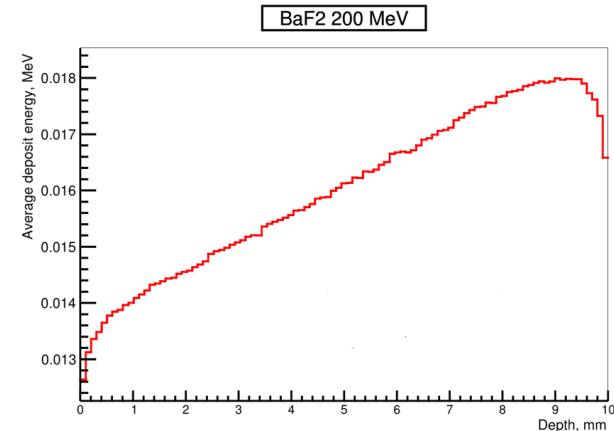
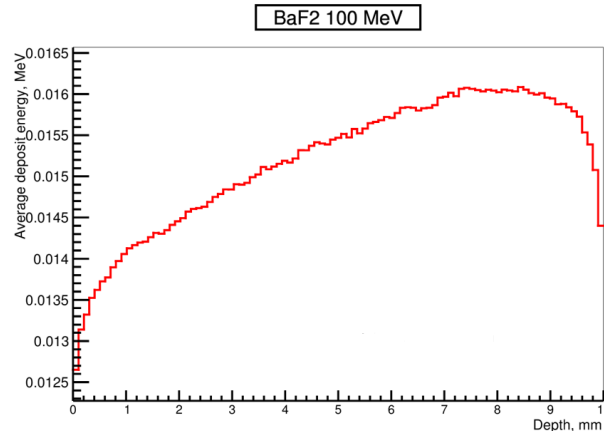
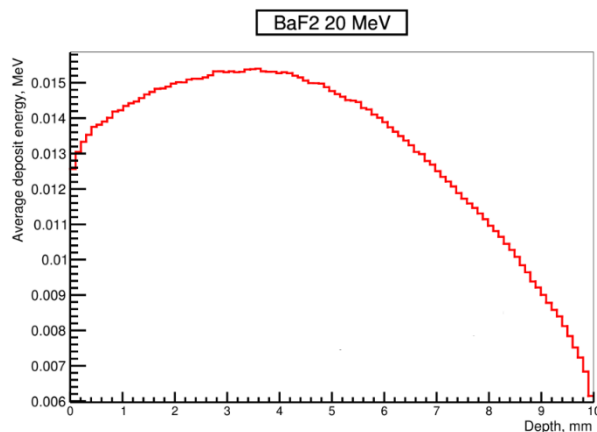


Only every fifth electron leaves energy in the tested cube

Longitudinal energy losses in a cube

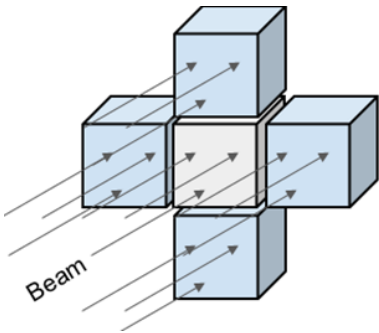


- The cube was “divided” into 100 slices perpendicular to the beam direction
- The electron beam is uniformly distributed over the face of the cube
- At $E=20$ MeV, the deposited energy decreases along the depth of the cube

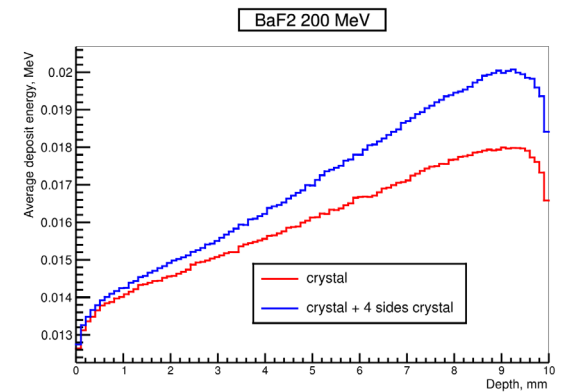
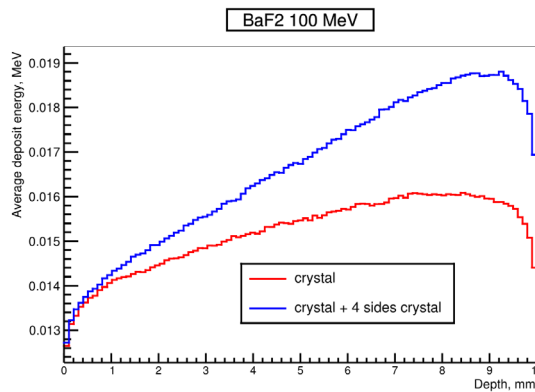
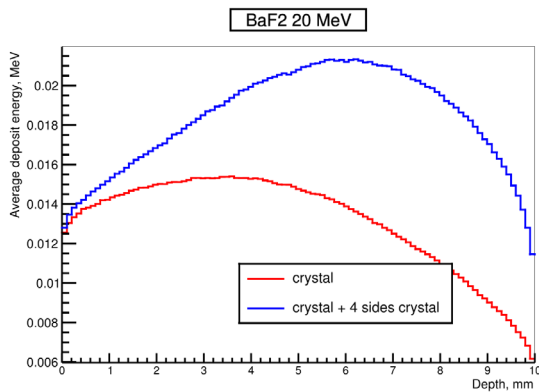


Only every fifth electron leaves energy in the tested cube

Longitudinal energy losses in a cube with four neighbors



- Four neighboring cubes do not improve situation essentially
- We need to try other methods to uniformly irradiate the samples (scanning the beam or moving the samples in the beam)



Summary

- Four crystal samples, one pure BaF₂ and three samples doped with yttrium in the proportion of 1 at.%Y, 3at.%Y and 5at.%Y, produced by SICCAS, were irradiated with neutron beam at IBR-2M reactor at JINR. About 2.3×10^{14} n/cm² (E>1MeV) passed through the samples
- All samples after irradiation had a decrease in light output. Light output loss of pure BaF₂ crystal is about 7%. The light output loss of Y-doped crystals is almost 2 times higher than that of pure BaF₂.
- In yttrium doped samples the light output loss of the fast emission component is 2-3% higher than that of the slow emission
- The simulation was carried out to assess the uniformity of irradiation of the samples in the electron beam.
- We plan to irradiate samples in an electron beam at the Linac-200 accelerator at JINR in a few months