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”Finger” structure of tiles in CMS Endcap Hadron Calorimeters

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Abstract

Two CMS Endcap hadron calorimeters (HE) have been in operation for several years and contributed substantially to the success of the CMS Physics Program. The HE calorimeter suffered more from the radiation than it had been anticipated because of rapid degradation of scintillator segments (tiles) which have a high radiation flux of secondary particles. Some investigations of scintillators have shown that the degradation of plastic scintillator increases significantly at low dose rates. A proposal to upgrade up-grade the HE calorimeter has been prepared to provide a solution for survivability of the future LHC at higher luminosity and higher energy. A finger-strip plastic scintillator option has many advantages and is a lower cost alternative to keep the excellent HE performance at high luminosity. Measurements have been performed and this method has proved to be a good upgrade strategy.

"Finger" structure of tiles in CMS Endcap Hadron Calorimeters

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Abstract

Two CMS Endcap hadron calorimeters (HE) have been in operation for several years and contributed substantially to the success of the CMS Physics Program. The HE calorimeter suffered more from the radiation than it had been anticipated because of rapid degradation of scintillator segments (tiles) which have a high radiation flux of secondary particles. Some investigations of scintillators have shown that the degradation of plastic scintillator increases significantly at low dose rates. A proposal to upgrade up-grade the HE calorimeter has been prepared to provide a solution for survivability of the future LHC at higher luminosity and higher energy. A finger-strip plastic scintillator option has many advantages and is a lower cost alternative to keep the excellent HE performance at high luminosity. Measurements have been performed and this method has proved to be a good upgrade strategy.

1. Introduction

The earliest light yield measurements have shown that the HE scintillator /WLS fibers will have only moderate radiation damage up to 500 fb^{-1} (10 years of LHC operation at the design luminosity) [1, 2]. In order to provide the HE operation at the LHC High Luminosity (3000 fb^{-1}), a limited number of tiles in high-eta, in the front section of HE would have to be replaced.

A technical proposal to upgrade the endcap hadron calorimeters (HE) is proposed to provide a solution for its survivability at future LHC higher luminosity. A finger-strip plastic scintillator version [3, 4, 5] has many advantages and is a lower cost alternative to keep the excellent HE performance at high luminosity.

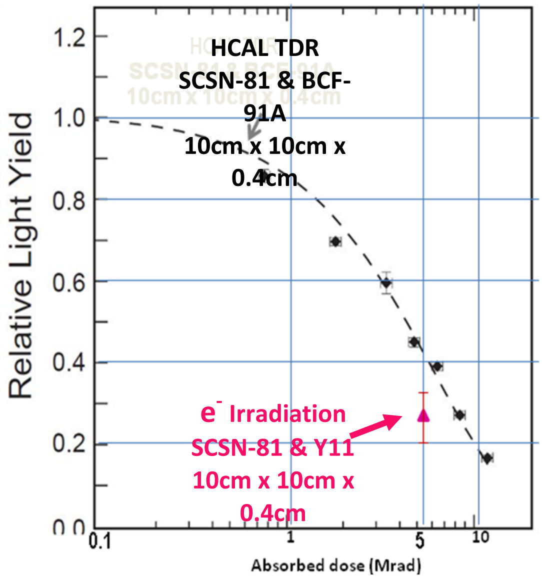


Fig. 1. The comparison of relative light yields of tile/fiber assemblies as a function of the absorbed dose (◆ - TDR results; ▲ - the RDMS result).

Our recent measurement of the tile with a sigma type groove with WLS fiber irradiated by electrons to 5 Mrad is shown in Fig. 1 [6]. The relative light yield from the main tile is compared with the previous values presented in HCAL TDR using Cobalt-60 gamma source. Our results are consistent with the measurements shown in TDR. Note that in these measurements, the neutron damage has not been included since the samples were exposed only to a gamma source.
Several previous investigations of the scintillator radiation hardness have shown a dependence of scintillator degradation with a radiation dose rate [5, 7]. Fig. 2 shows the dependence of the light yield from the samples on the dose rate. The light yield degradation under irradiation turns out to be substantially greater at lower rates. The KIPT data are in a good agreement with the earlier experimental results [7]. Since the estimated dose rate at the HE for the HLLHC conditions will not exceed ~1 krad/hr, the dose rate effect being discussed here needs to be taken into account in the HCAL Upgrade Project.

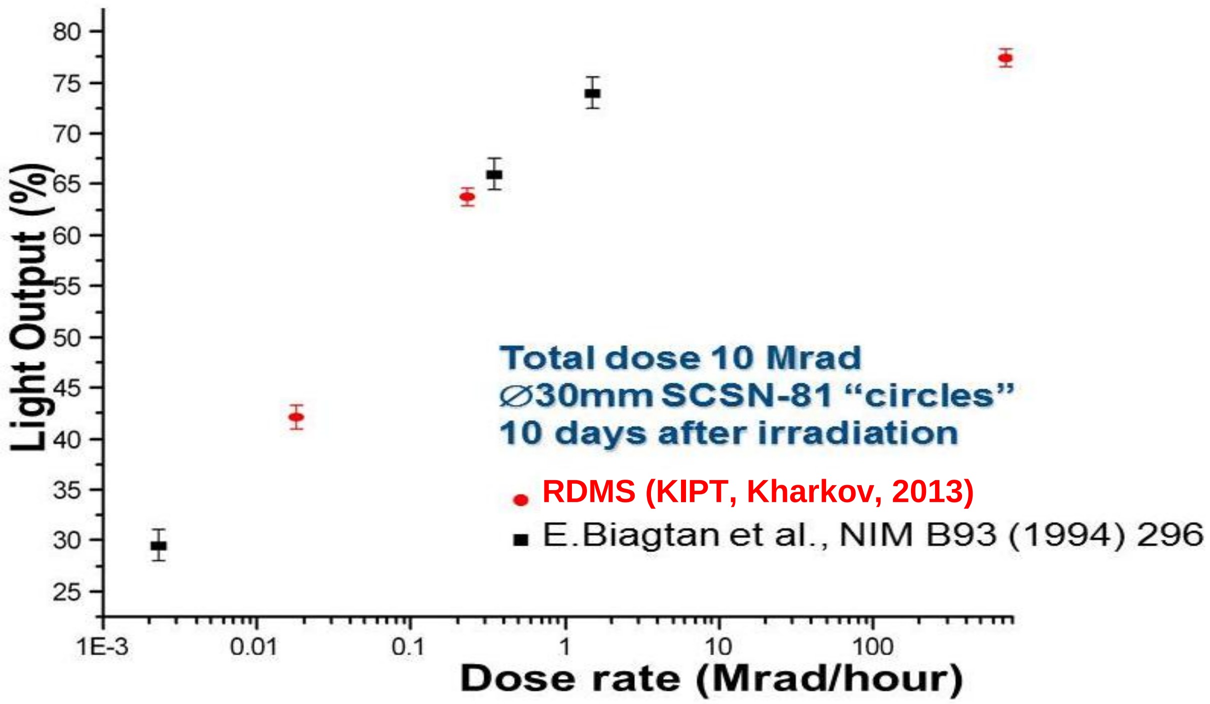


Fig. 2 Light yield degradation under irradiation vs. dose rate for SCSN-81 samples irradiated to 10 Mrad.

Degradation of the scintillators, WLS fibers which collect the light and clear fibers which transfer the light to Photo Detector (PD) means decreasing in the number of photons arriving at the PD. An installation of PD with a better photo-sensitivity like SiPM instead of HPD allows to prolong the life of scintillation detectors. A better design of the plastic detector (the shape and position of WLS fibers) should provide better light collection. We propose to construct several tiles of HE from several (4, 8) strips – "fingers". "Finger" type tiles provide a considerably better light collection as opposed to the current design. The CMS tiles were produced with SCSN-81 scintillators. Now production of this scintillator has been halted by Kuraray. Two similar commercial scintillators are available: BICRON-408 (BICRON Co.) which needs WLS Y11 from Kuraray Co. and EJ-260 (ELJEN Co.) which also needs WLS O2 produced by Kuraray Co.
This paper describes the experimental results which have been obtained by several groups of RDMS. The investigations were aimed at studying the effect of gamma, neutron and electron radiation and their dose rates on samples of commercially available scintillators like BICRON and EJ-260.

Plastic scintillator damage is a complex function of Dose and Dose Rate and experimental studies are should give answers the following three issues:

1. Radiation damage of “fingers” up to 2500-3000 fb^{-1} (survivability by the end of LHC).
2. Radiation damage of the existing sigma tiles at 700 fb^{-1}(survivability to the LS3).
3. Understanding of SCSN81/Y11 Radiation damage at 30 fb^{-1}.

2. HE description.

There are two endcap hadron calorimeters at each end of CMS and they are a part of the hadron calorimeter (HCAL) system of CMS [8, 9]. Both HE’s are fine segmented detectors. Each HE is segmented into individual calorimeter cells along three specialized coordinates: η - pseudorapidity, φ - azimuthal angle and Z along the beam line (see Fig. 3). Each endcap has 18 azimuthal (20°) sectors. Every sector has 18 depth layers of scintillators inserted inside brass absorbers. The sector in each layer contains two scintillator trays (megatiles) which are specific in size to that layer. A single megatile covers ten degrees in the azimuth. A structure of a single megatile defines a transversal granularity of the HE and is divided into 19 cells along η-coordinate and covers η from 1.3 to 3.0. The HE cells with η = 2.3 – 3.0 are very close to the beam line and are exposed to excessive levels of secondary particles. The high luminosity of the LHC (~10^{34} cm^{-2} s^{-1}) leads to production of large amount of secondary particles. The two endcaps cover the space containing about 34% of the particles produced in pp collisions in the center of CMS [10]. The megatiles (sectional scintillation detectors) of HE irradiated with secondary particles become degraded by the absorbed radiation dose that is proportional to the total luminosity delivered to CMS.

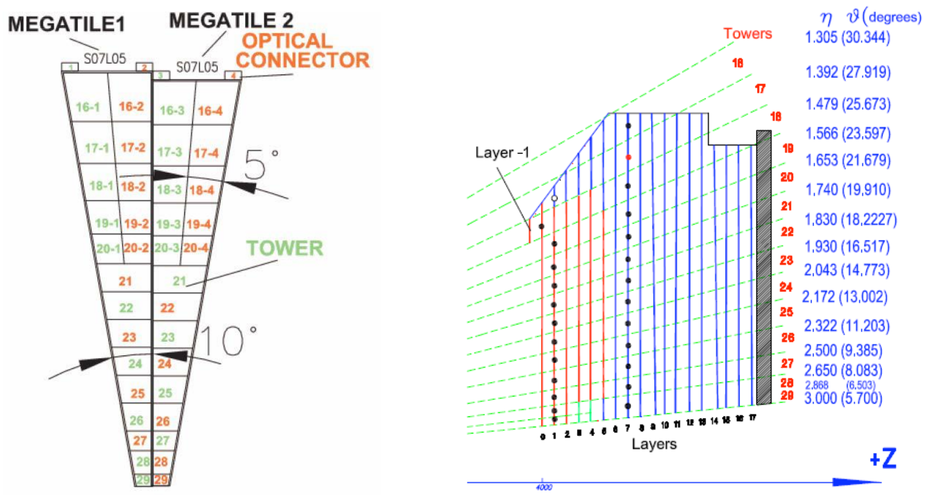


Fig. 3. HE segmentation of two adjacent HE scintillator trays and the numbering scheme of layers.

3. A proposed solution for "finger" option.

The improvement in light collection is possible by reducing the size of the segment of scintillator [3]. In this case, first, the impact of scintillation darkening is reduced because the average path of light from the place of its origin to WLS fibers becomes shorter, and second, the length of WLS fibers also becomes shorter, and, hence, the loss of light caused by its darkening is decreased. Dividing of tiles of the same tower into the equal number of segments keeps the existing geometric proportions. Each "finger"-segment has its own WLS fiber (see Fig.4a). The light from WLS fibers from all segments of the tile is collected optically or electrically (after conversion of light to the electrical signal).

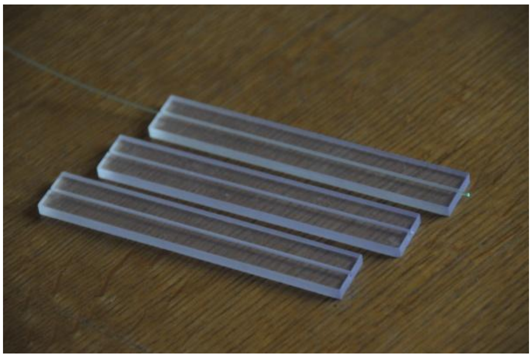


Fig. 4a. A view of the "finger" scintillator with WLS fiber inside.

It is proposed to replace 4 tiles (26, 27, 28, 29) in each megatile of the first 5 layers (0 – 4) with the "finger" design. Fig. 4b shows these changes.

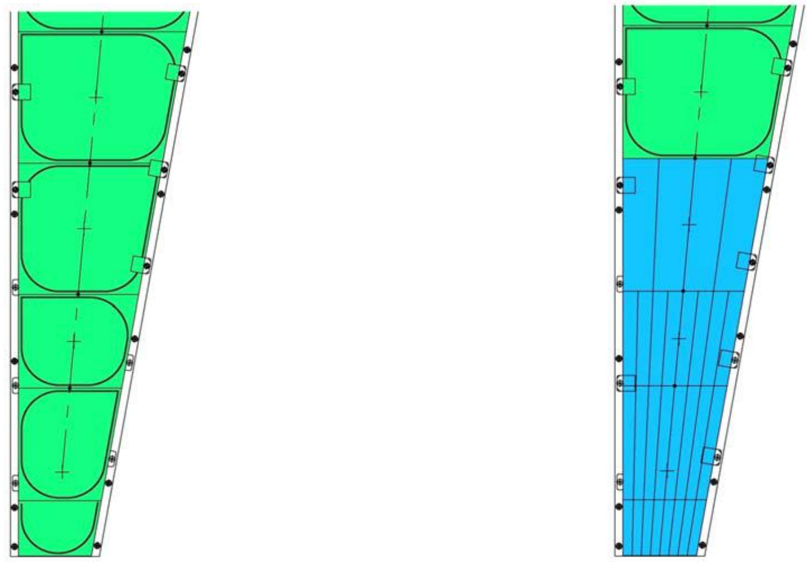


Fig. 4b "Finger" scintillator concept.

4. Experimental studies of the "finger" type scintillator detector.

The series of measurements of the "finger" scintillators detect the dependencies of light output vs. the absorbed radioactive dose were performed. The results have been obtained from the measurements of light outputs from the irradiated samples exposed to different absorbed doses and dose rates. Two sets of different "finger" scintillators BICRON, EJ-260 were used for the irradiation. Several teams of RDMS performed these studies for different absorbed doses and dose rates. ^{60}Co (INP/Tashkent, NC HEP/Minsk) was used for gamma irradiation and reactor IBR-2 (JINR/Dubna) - for neutron irradiation. The YLS fibers were not irradiated.

4.1. Experimental results received with gamma sources.

Some of the samples of BC408 and EJ-260 scintillators were irradiated by gamma source ^{60}Co in the range of absorbed doses from 5 to 30 Mrad for various dose rates.

A part of samples BC408 and EJ-260 were exposed at the gamma-irradiation facility of the Institute of Nuclear Physics (INP) in Tashkent.

That facility contains 622 Co-60 sources (with the total activity about 85,000 Cu) uniformly surrounding the irradiation zones in three 5m deep underground wells filled with cooling water. There are 9 irradiation dry channels with a diameter from 5 to 60 cm and dose rates from 0.022 to 0.600 Mrad/h. The temperature in each irradiation channel is within (30-50)^0 C and the gradient of gamma-field in each used channel is within 8%. One should remind that Co-60 isotope emits gammas with the energy of E = 1.173 MeV and E = 1.333 MeV. The gamma-facility is shown in Fig. 5.

Fig. 5. View of the gamma-facility in INP (Tashkent).

A set of samples of BC408 and EJ-260 scintillators was irradiated in the range of absorbed doses from 5 to 25 Mrad for various dose rates.

The doses and dose rates were calculated by using the facilities existing program as well as directly measured with various sets of certified film and glass dosimeters place in the same batch together with irradiated samples. Also the spectrophotometry was done for each type of scintillators before and after irradiation. For measurements two types of spectrophotometers were used: the two-armed M40-Zeiss (the optical range in 200-800 nm) and SF-56_LOMO (the optical range in 190-1100 nm). The data of optical measurements will be presented in another paper.

The measurements of the light yield from all irradiated samples have been performed in Dubna with a ^{106}Ru beta-source and at MEPhI with a ^{90}Sr beta-source. The two measurements are very similar. Here we describe the measurements with the ^{90}Sr beta-source. Fig. 6 shows a layout of the measurements. The light in the samples was excited by electrons from the beta-source triggered with a trigger counter. The trigger counter threshold was about 0.5 MeV. The beam size on the strip surface was about 1.5 mm FWHM. It was checked that the energy deposited by an electron in the scintillator strips in this setup is very close (with the accuracy of 10%) to the energy from cosmic particles (MIP).

The 105 mm long Y11 Wave Length Shifting (WLS) fiber was used for light collection in all BC-408 strips while the 145 mm long O2 WLS fiber was used for the EJ-260 scintillator strips. The WLS fibers were located in a groove in the middle of the strips. A SiPM (MPPC S10362-13-050C) was used as a Photo Detector. The SiPM was operated under stable conditions of bias voltage (71.2 V) and temperature (20°C). These conditions correspond to the overvoltage of 1.7 V and a crosstalk of about 22%. SiPM signals were amplified and digitized with a LeCroy 2249A ADC. The ADC gate width was set to 100 ns.

Fig. 7 shows examples of the amplitude distributions for a BC-408 strip irradiated to 25Mrad with different dose rates. The strip response drops with the decrease of the dose rate. A fit of data for highest irradiated strips was difficult because of the vicinity of the pedestal (see Fig. 7d). Therefore we calculated the strip response by averaging amplitudes above the pedestal. This procedure gives about the 3% higher value than the Landau distribution peak position in case of non-irradiated strips where the peak is well separated from the pedestal.

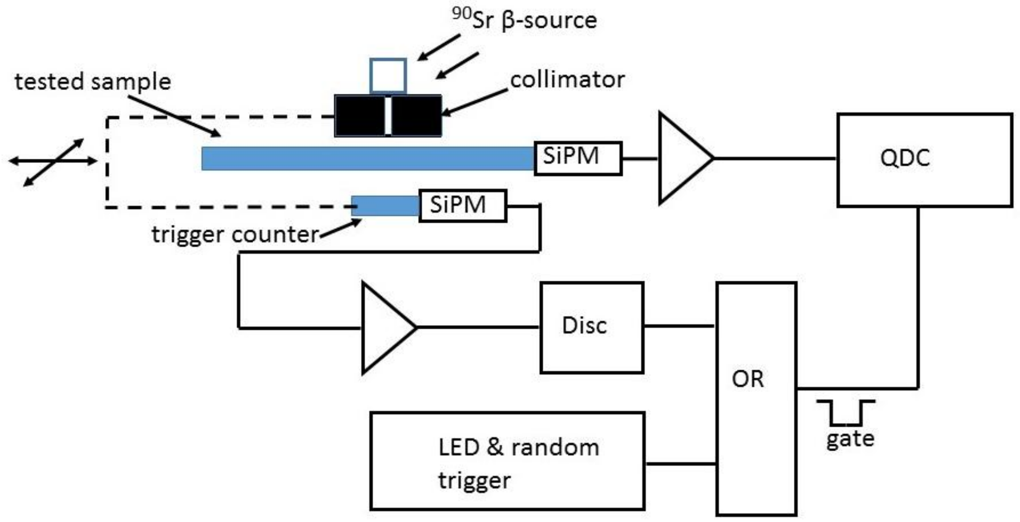


Fig. 6. Test setup for the measurements of light yield from scintillator strips using a ^{90}Sr beta-source.

The strip response depends on a distance from the track to the WLS fiber. Therefore we averaged the response across the strip. A transverse scan of each strip was made with a step of 1 mm at a 25 mm distance from the strip longitudinal edge (see Fig.8). Points within 2 mm from the strip sides were not used in averaging since the trigger conditions varied because of the finite beam size. The strip response along the strips was practically constant except the edge effects.

Figs. 9 and 10 show the light yield for strips 29 irradiated by the ^{60}Co source to 20Mrad and 25 Mrad with different dose rates.

The accuracy of our results was estimated by the spread in the light yield of 8 non-irradiated BC-408 strips (2 for each strip geometry) and 8 non-irradiated EJ-260 strips (2 for each strip geometry). This resulted in the value of 8% error for an individual measurement. Obviously this is only an estimate of our accuracy. These estimated errors are shown in Figs 9 and 10 for EJ-260 points only. The errors for BC-408 points are similar. They are not shown in figures in order to reduce the clutter.

Figs 11 and 12 show the light yield of the irradiated strips for sector 29 divided by the light yield of the non-irradiated strips. Normalization for the relative light yield measurements was done using the average value of two non-irradiated strips in order to reduce the errors. The estimated errors are shown for EJ-260 points only as in Figs 9 and 10.

Fig. 13 shows the light yield for the sector 29 strips irradiated to 25Mrad and read out with a WLS fiber irradiated to 25 Mrad as well. The fiber irradiation was performed on the 6 MeV electron beam with the dose rate of about 500 Mrad/hour. The light yield measurements were performed 450 hours after the fiber irradiation. The far end of the fiber was painted with a silver paint. The paint increases the light yield by a factor of about 1.45.

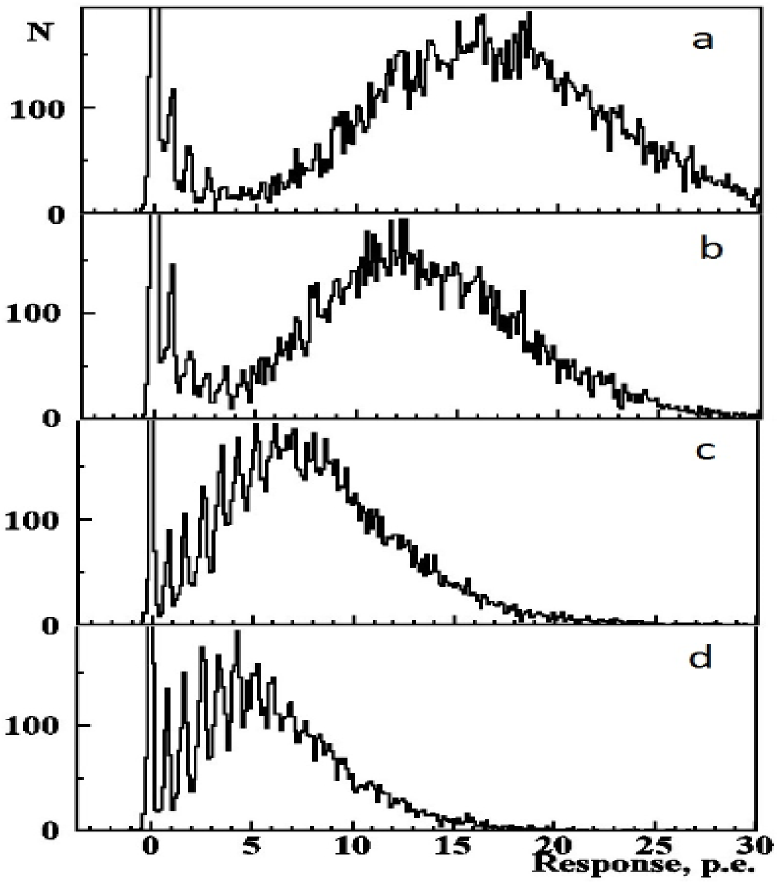


Fig. 7 Examples of amplitude spectra from sector 29 strips (BC-408) irradiated to 25 Mrad with different dose rates: 0.6 Mrad/hour (a), 0.2 Mrad/hour (b), 0.04 Mrad/hour (c), 0.02 Mrad/hour (d). The first peak in all figures is a pedestal.

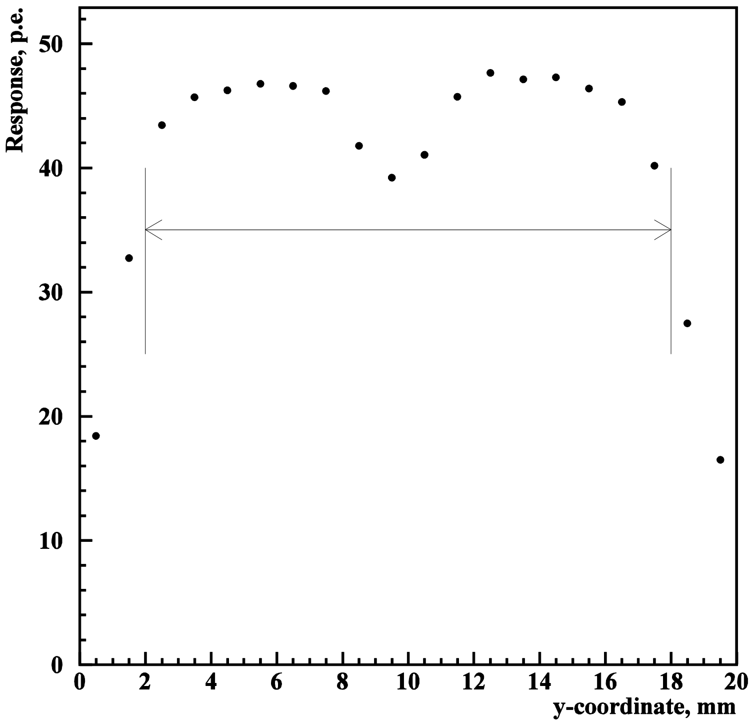


Fig. 8 Example of the light yield measurement across the sector 26 strip (BC408, 0 Mrad). Arrows show the strip size. Reduction of the response near the strip edges is due to a non perfect trigger because of the finite beam size.

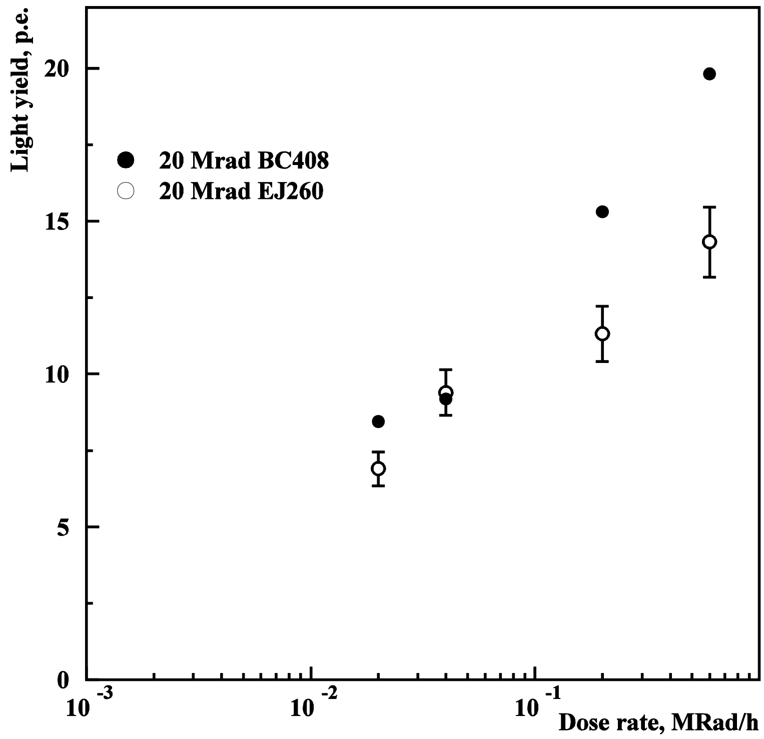


Fig. 9 Light yield from sector 29 strips irradiated to 20 Mrad with different dose rates.

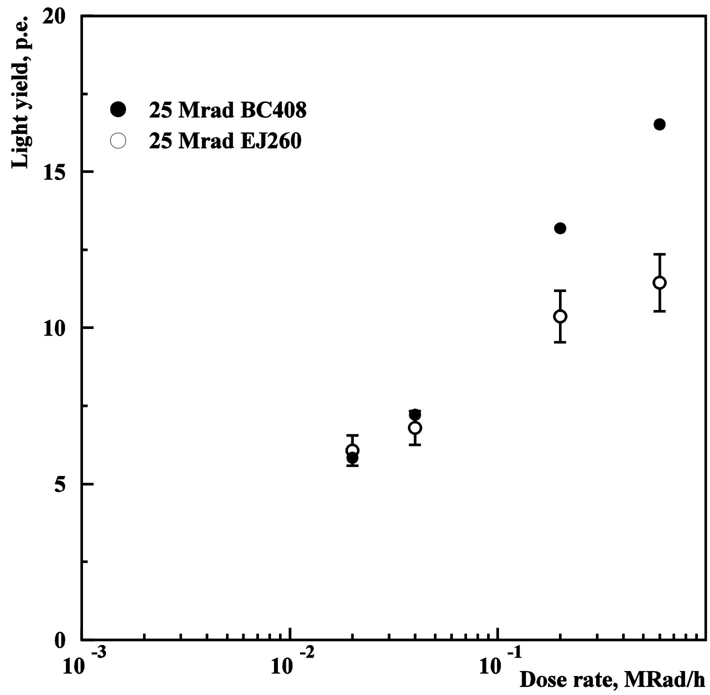


Fig. 10 Light yield from sector 29 strips irradiated to 25 Mrad with different dose rates.

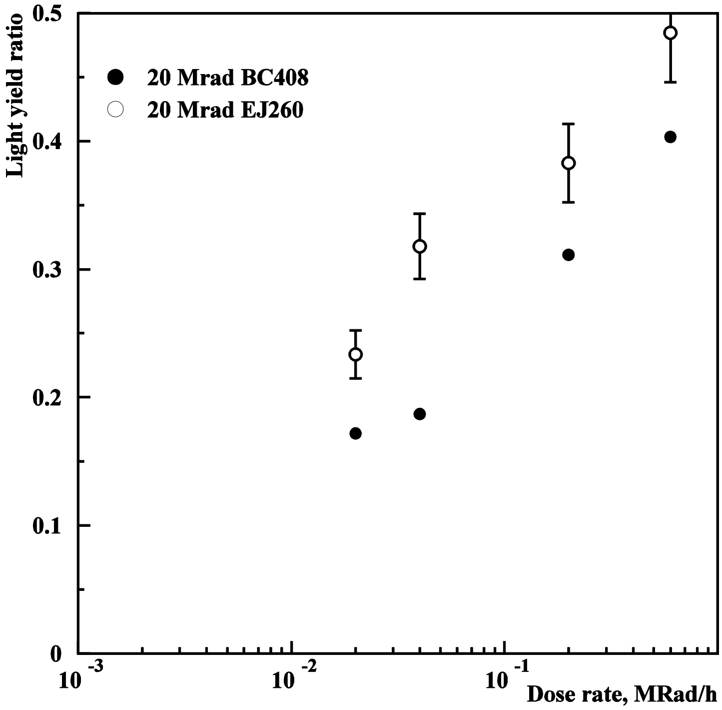


Fig. 11 Relative light yield from sector strips irradiated to 20 Mrad with different dose rates.

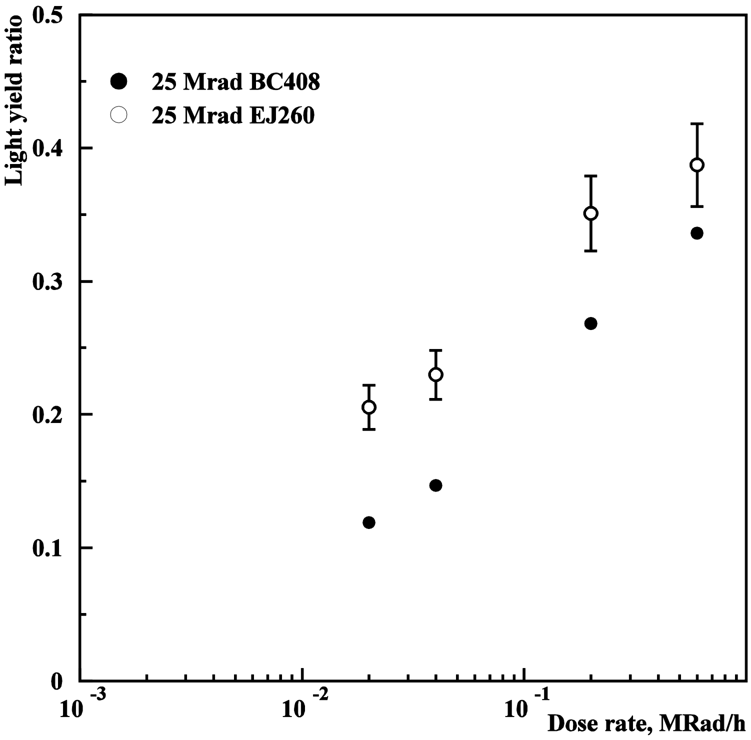


Fig. 12 Relative light yield from sector 29 strips irradiated to 20 Mrad with different dose rates.

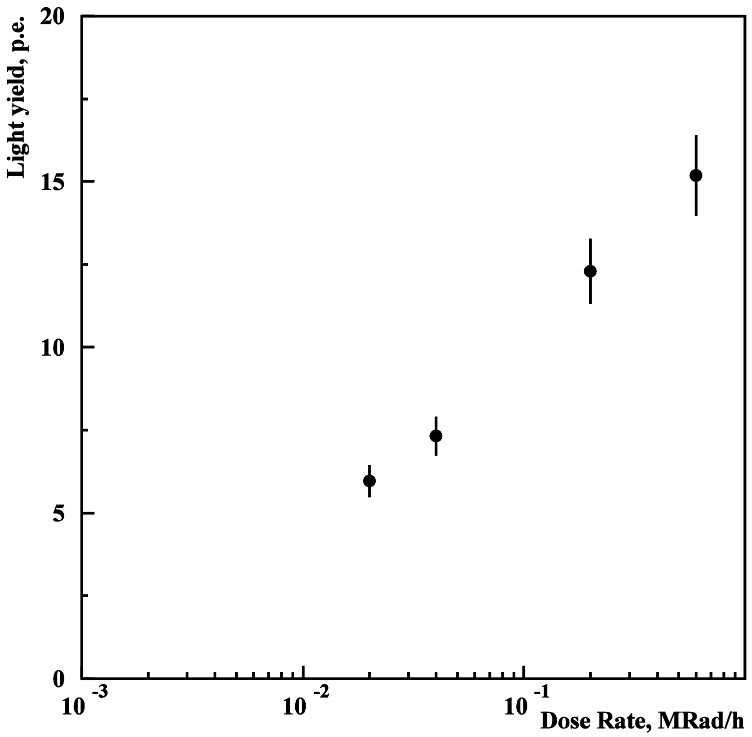
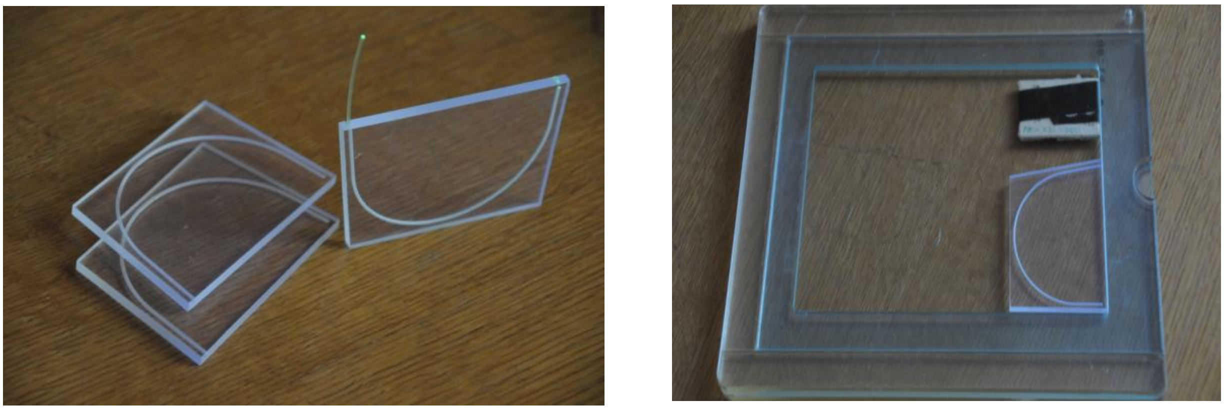


Fig. 13 Light yield from the sector 29 strip (BC-408) irradiated to 25 Mrad with different dose rates and read out with the Y11 fiber irradiated to 25 Mrad. The fiber far end was painted with a silver paint.

The second set of gamma irradiation has been done by the team from the National Center for Particle and High Energy Physics (Minsk, Belarus). Gamma irradiation of the samples was performed in the State Scientific Institution "The Joint Institute for Power and Nuclear Research - Sosny" of National Academy of Sciences of Belarus. The gamma source is ^{60}Co with the activity of 0.2 MCi. Fig. 14a shows some samples of sigma tiles from tower 29 of Layer 1 made from SCSN-81, one sample contains WLS fiber. Fig. 14b shows a sample without WLS fiber which is laid inside the plastic container together with the film dosimeter ready for irradiation by gammas from the ^{60}Co source.



a) b)

Fig. 14 a) Tile 29 with WLS fiber. b) Tile 29 made from SCSN-81 without WLS fiber laid inside the plastic container together with the film dosimeter is ready for irradiation by gammas from the ^{60}Co source.

One set of samples received a total absorption dose 250 KRad and the other - 600 KRad. The dose rate was varied from sample to sample.

Fig. 15 shows the dependence of the relative amplitude vs. the dose rate for the sigma type SCSN-81 scintillator. Straight lines show the extrapolations of experimental results for the region of very small dose rates more close to the reality of HE but could not be reachable experimentally.

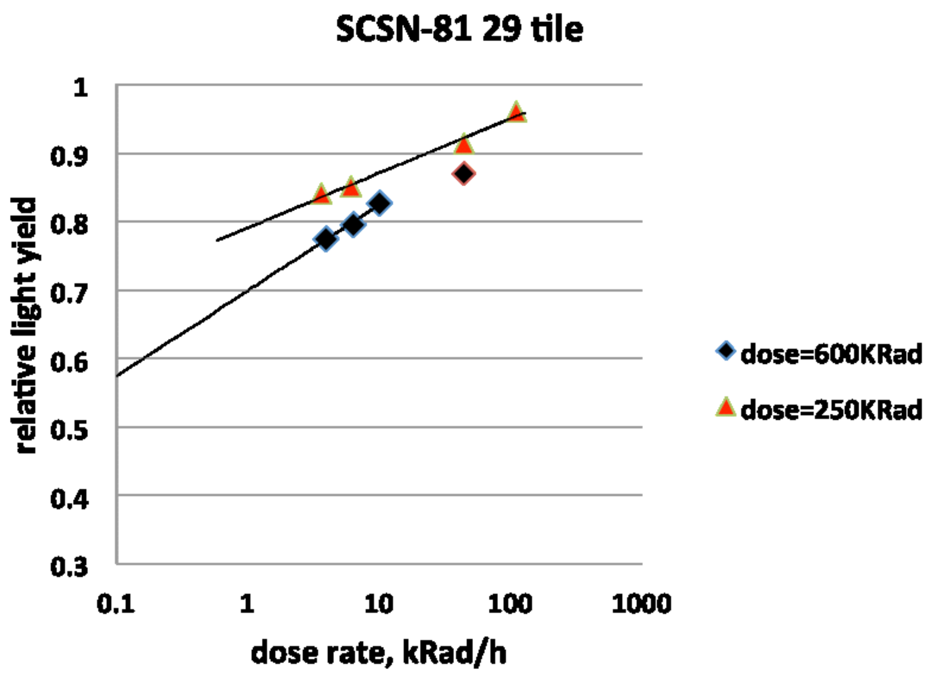
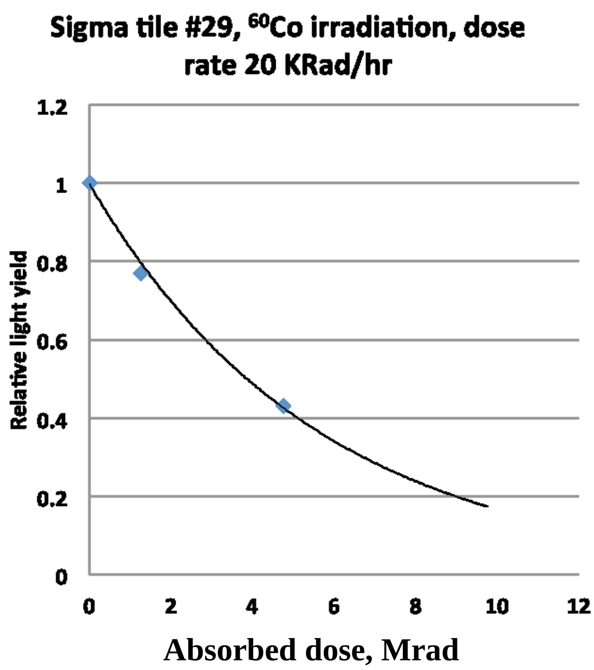


Fig. 15 Dependence of the relative light yield of the SCSN-81 sigma tile #29 vs. the dose rate 7 days after irradiation

Some samples were irradiated for a larger dose (several Mrad) to define dependencies of the light yield (relative and in photoelectrons) vs. the total absorbed dose and to evaluate the radiation damage of the existing sigma tiles at 700 fb^{-1} (survivability by the LS3) for a low dose rate of 20 KRad/h (see Fig.16).



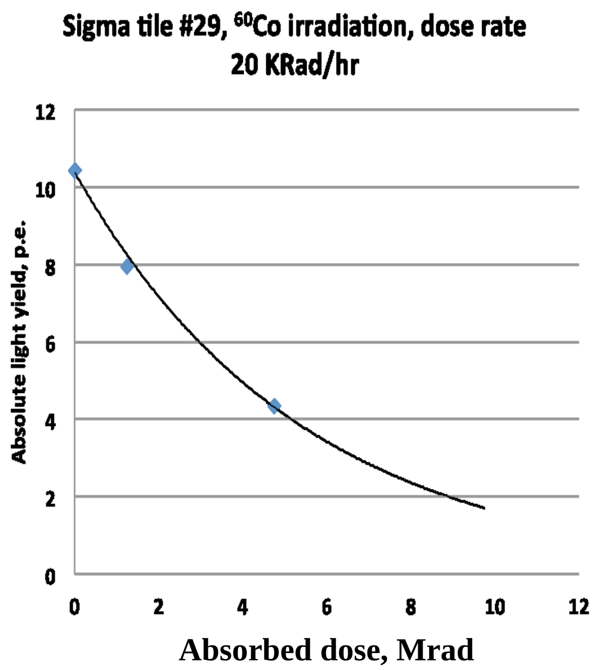


Fig. 16 Dependencies of the light yield (relative and in photoelectrons) vs. the total absorbed dose and the estimated light yield for the dose up to 10 Mrad

4.2. Experimental results received with neutrons.

The IBR-2M (JINR/Dubna) facility [10] with its unique technical approach produces one of the most intensive pulse neutron fluxes at the moderator surface among the world's reactors:

- Primary flux: n(85%)+γ(15%) 10^9-10^{11} $cm^{-2}s^{-1}$ (<En> ~ 1MeV).
- Dose rate: 500 $kRad \cdot h^{-1}$(<Eγ> ~ 1.5-2 MeV).
- Fluence: ~$3 \cdot 10^{15}$ n/cm^2 in per run.

Fig. 17 shows the neutron instrumentation at the IBR-2 reactor.

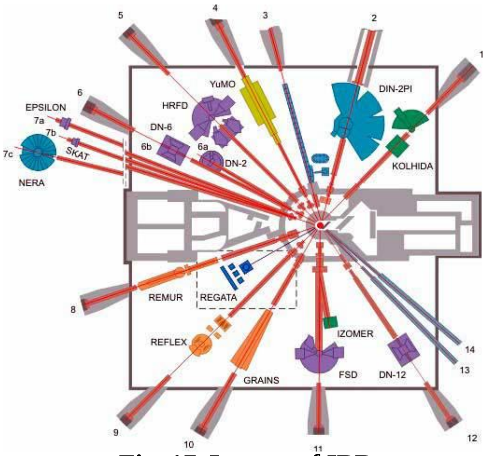


Fig. 17. Layout of IBR.

A set of scintillator samples (SCSN-81, Bicron-408 and EJ-260) was irradiated by neutrons of IBR-2M from 22.09.2014 till 6.10.2014.

The first stage of irradiation includes exposure of two sets:

- The samples SCSN-81 (tile #29,with and without lateral face painting); two Bicron-408 “fingers” (tile #29, with and without lateral face painting); single EJ-260 “finger” (tile #29) for the dose 6.5 of Mrad registered by the film dosimeter. The estimate of the total neutron fluence is ~ 2 x 10^{15} n/cm^2 measured by a silicon monitor. Face painting is white paint at all the edges of the scintillators.
- Single scintillator SCSN-81 (tile #29, without lateral face painting) for the dose of 2 Mrad registered by the film dosimeter. The estimation of the total neutron fluence is ~ 0.6 x 10^{15} n/cm^2 measured by a silicon monitor.

The results of measurements in comparison with the Tashkent results of gamma irradiation are shown in Fig. 18. A visible decrease of the relative light yield from the neutron flux (fluence 2.34 x 10^{15} n/cm^2) reaches a factor of 2 for the both types of scintillators.

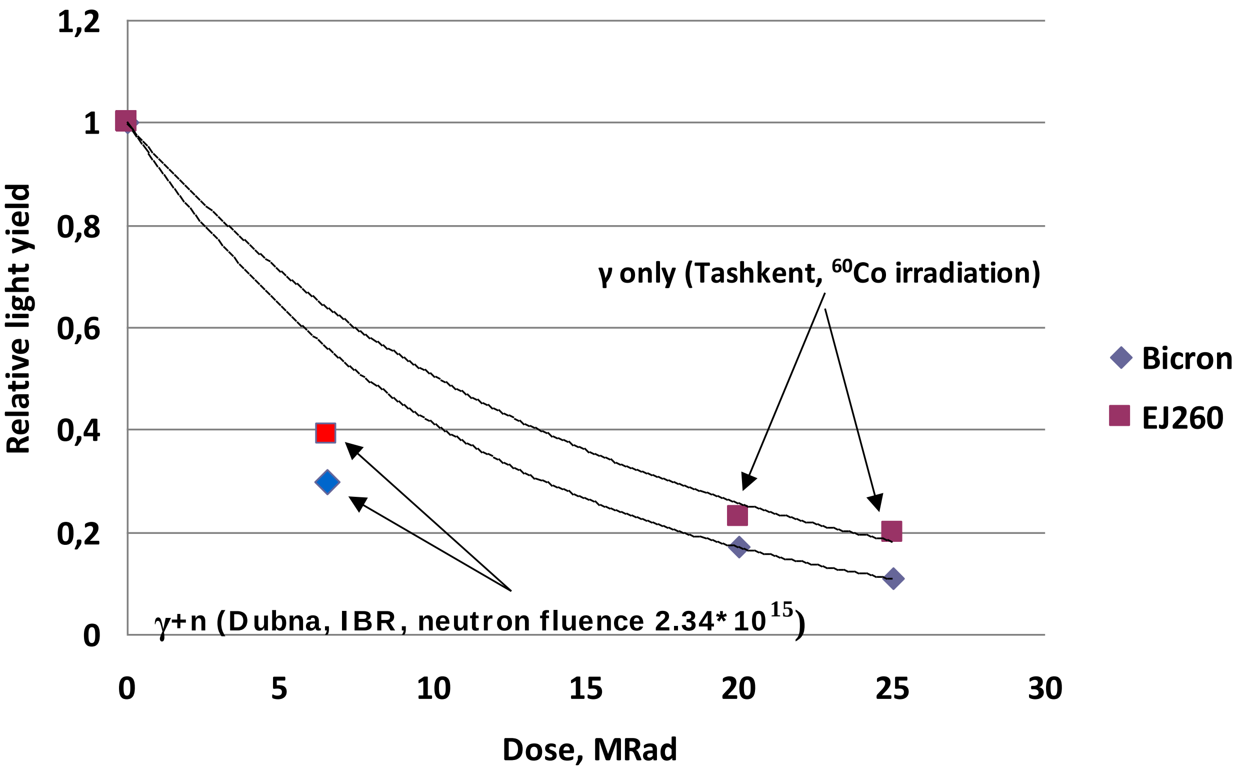


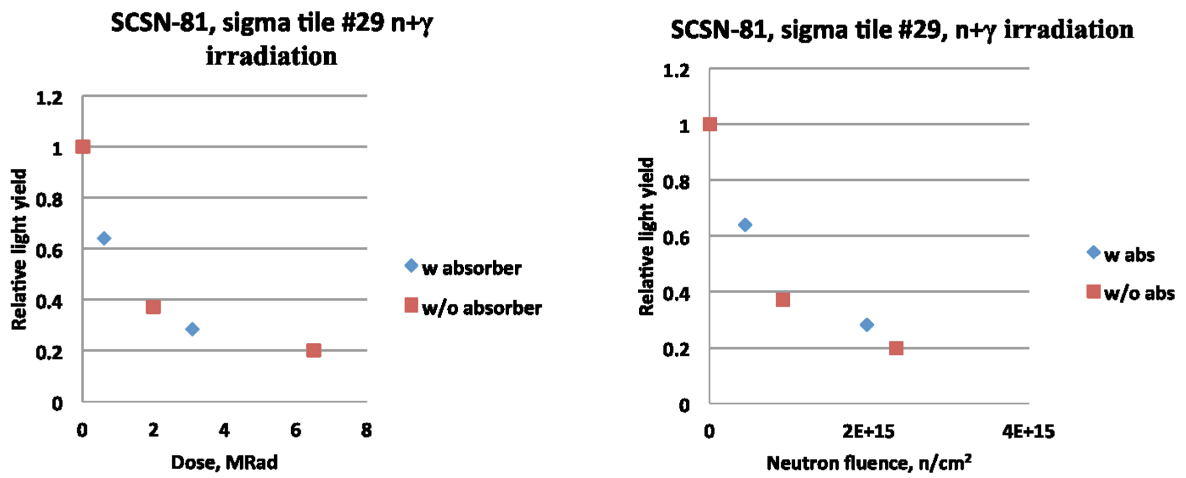
Fig. 18 Comparison of the experimental data from gamma-neutron irradiation (IBR/Dubna) and from gamma irradiation (^{60}Co, Tashkent). Relative light yield for a finger of tower 29 vs. dose for dose rate 20 KRad/hr.

The second stage of irradiation also includes the exposure of two sample sets:

- Plastics SCSN-81, BICRON-408, EJ-260 and shifters Y11, O2 together with pieces of brass (some imitation of presence of the brass absorber near the plastic detector).
- Plastics SCSN-81, BICRON-408, EJ-260 and shifters Y11, O2 together with pieces of brass (some imitation of presence of the brass absorber near the plastic detector).

All zones were equipped with film dosimeters (absorbed dose) and silicon monitors (neutron fluence).

Fig. 19 shows dependencies of the relative light yield in presence of the brass absorber and without it. The presence of brass pieces near the samples has not shown considerable changes in the values of the measured light yield.



a) b)

Fig. 19 a) Dependencies of relative light yield in presence of the brass absorber and without it for the dose values measured by film dosimeters. b) Dependencies of the relative light yield in presence of the brass absorber and without it for the dose values measured by Si detectors.

5. Conclusions.

A series of experimental studies were performed by several RDMS teams. The main results are as follows:

- “Finger” option provides the HE functioning for high LHC luminosity.
- Unpredictable degradation of the HE plastic scintillators at 30 fb^{-1} can be explained by the dose rate effect.
- The experimental results have shown visible influence of neutrons with the fluence of 2.3×10^{15} n/cm^2 to the relative light yield (factor 2).
- Low influence of induced radioactivity from the brass absorber.

References:

1. CMS collaboration. “CMS, The Hadron Calorimeter Technical Design Report,” CERN/LHCC 97-31 CMS TDR 2 (June 1997).
2. Jim Freeman. “Hadron calorimeters for future hadron colliders”, INNOVATIVE DETECTORS FOR SUPERCOLLIDERS. Proceedings of the 42nd Workshop of the INFN ELOISATRON Project. Held 28 September-4 October 2003 in Erice, Italy. Published by World Scientific Publishing Co. Pte. Ltd., 2004, pp. 362-377.
3. S.V. Afanasiev, P. de Barbaro, I.A. Golutvin et al. "Improvement of radiation hardness of the sampling calorimeters based on plastic scintillators", Nuclear Instruments and Methods in Physics Research A 717 (2013) 11–13.
4. S.V. Afanasiev, I.F. Emeliantchik, I.A. Golutvin, L.G. Levchuk, A.V. Litomin et al., "An improvement of a radiation hardness of the CMS Hadron Endcap Calorimeters under increased LHC luminosity", CERN CMS Note-2012/002 (2012) 8 p.
5. S.V. Afanasiev, P. de Barbaro, A.Yu. Boyarintsev et al. "HE upgrade beyond phase 1. Finger scintillator option", CERN CMS Note-2014/001 (2014) 16 p.
6. S.V. Afanasiev, I.F. Emeliantchik, I.A. Golutvin et al. "An improvement of a radiation hardness of the CMS Hadron Endcap Calorimeters under increased LHC luminosity", CERN CMS Note-2012/002 (2012) 9 p.
7. E. Biagtan, E. Goldberg et al., "Effect of gamma radiation dose rate on the light output of commercial polymer scintillators", NIM B93 (1994) p. 296-301.
8. CMS Collaboration. "The CMS Experiment at the CERN LHC", 2008 J. Inst. 3 S08004, DOI: 10.1088/1748-0221/3/08/S08004
9. CMS Collaboration. "Performance of the CMS hadron calorimeter with cosmic ray muons and LHC beam data", 2010 J. Inst. **5** T03012, DOI: 10.1088/1748-0221/5/03/T03012, arXiv:0911.4991
10. IBR-2 Pulsed Reactor. http://flnp.jinr.ru/34/