AN IMPROVEMENT OF A RADIATION HARDNESS OF THE CMS HADRON ENDCAP CALORIMETERS UNDER INCREASED LHC LUMINOSITY

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One very important aspect of an upgrade program of the Hadron Endcap Calorimeters (HE) is connected with the need to provide a radiation hardness of individual detectors (tiles), located in the first five layers of each HE for towers 23–29 (pseudorapidity range 2.0–3.0). Changing the method of light collection from the most irradiated scintillator tiles will provide a long-term usage of scintillator as a detector of HE under increased LHC luminosity. The experimental results of the measurements for the different assemblies (scintillator SCSN-81 and the WLS fiber Y11) irradiated with electrons ($E \approx 4$ MeV) are discussed.

INTRODUCTION

Two Hadron Endcap Calorimeters (HE) are the parts of the CMS Hadron Calorimeter (HCAL) and measure particles in the range of pseudorapidity $1.4 < \eta < 3.0$. The position of one of the detector parts (quarter slice) and some neighboring detectors with respect to the beam interaction point is shown in Fig. 1 [1]. HE is a sampling calorimeter. It uses the layers of scintillators to sample the energy deposition of hadrons in the layers of copper absorber [2]. The sampling layers of HE are oriented perpendicular to beam axis. Scintillator tiles of HE, which are closer to the beam, absorb the greater radiation dose.

A lifetime of the organic scintillators which are used in HE are dependent on the extent of their absorbed dose. Currently, several trends of development and upgrade of HE are defined. Main aspect is to provide a work of the detector's tiles in the fields of high radiation. The simulation results of radiation fields in the detector are given in the paper [3] and shown in Fig. 2. Radiation doses are given in Gray's units for the period

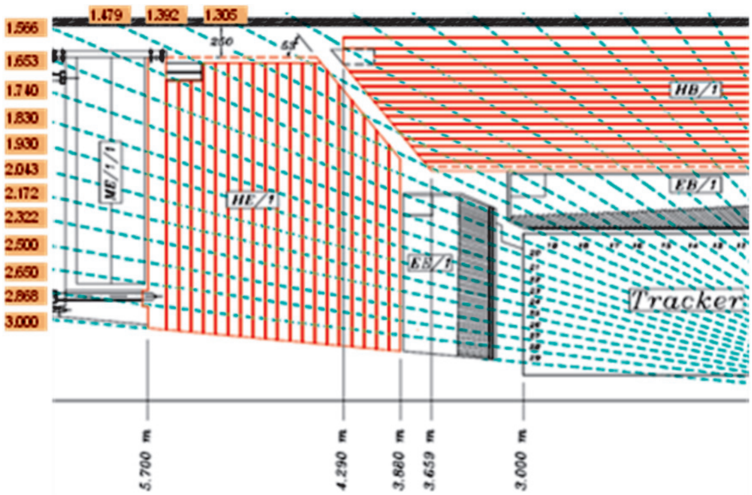

Fig. 1. A position of one of HE detector parts and its surroundings

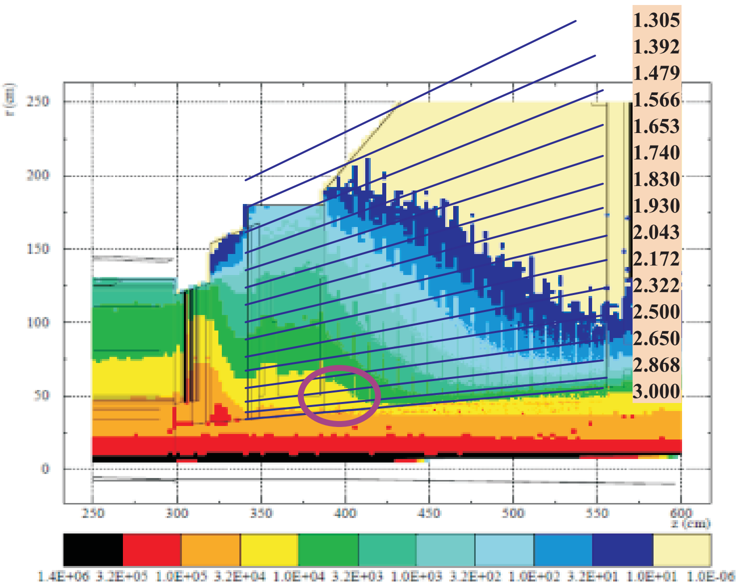

Fig. 2. Simulation of a dose map (Gy per 500 fb^{-1}) in the HE

of time which should provide an accumulation of experimental data for integrated luminosity of 500 fb^{-1}.

It means approximately 10 years of LHC operation. The figure shows that most of the irradiated part of HE is its section with the values of

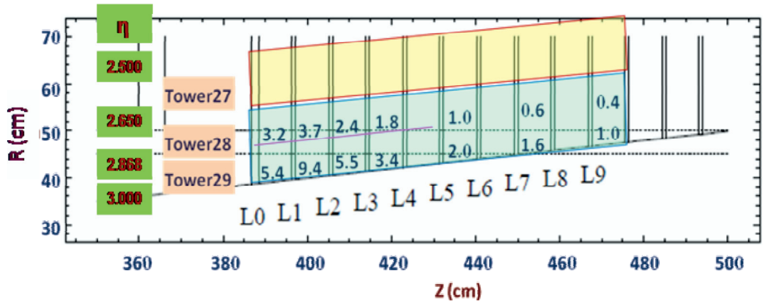

Fig. 3. A detailed view of front part of HE for big η

pseudorapidity η from 2.5 to 3.0 in the first few layers of HE. Figure 3 gives more detailed picture about position of tiles with big values of pseudorapidity η, their radial position and the absorbed doses (in Mrad) proposed by simulation in those tiles.

1. MAIN FACTORS OF LIGHT LOSS

Figure 4 shows the numbering scheme for the tiles in two adjacent scintillator trays (megatiles) [4]. They form a 20-degree HE sector in azimuth angle. The detector media of HE is a scintillator Kuraray

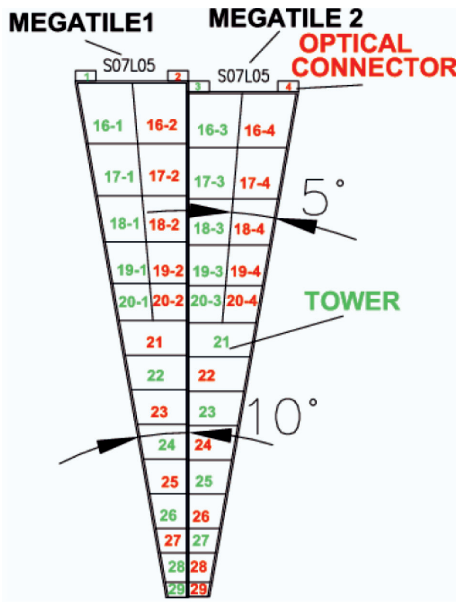

Fig. 4. Numbering scheme for the tiles in adjacent scintillator trays

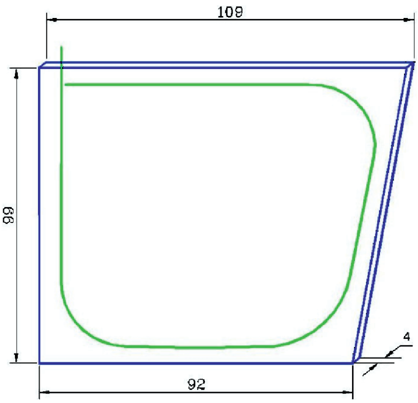

Fig. 5. Basic structure of a scintillator tile with WLS fiber

SCSN81. The light generated by charged particle crossing the scintillator is collected by Wave Length Shifting (WLS) fiber Kuraray Y-11. The WLS fiber exciting the scintillator is spliced to a clear fiber, the other end of which is glued onto an optical connector [5]. Then a light is transmitted to the pixel of the hybrid Photo Detector (HPD).

Figure 5 illustrates a shape of scintillator tile and position of WLS fiber. That sample has a trapezoidal shape with dimensions as a tile 27 in layer 1. The irradiation affects both the scintillator and WLS fiber. Degradation of the scintillators and WLS fibers means a decrease in the number of photons arriving at the Photo Detector. The factors of light loss with dose increase are the following:

1. Transmittance loss of scintillator (becomes yellow);
2. Transmittance loss of WLS fiber;
3. Degradation of scintillating ability;
4. Reducing of conversion efficiency of WLS fiber.

This report describes the activity connected with researches to improve the light collection from the most irradiated tiles of HE and that will allow increasing the radiation hardness of HE scintillators. We have prepared a number of different assemblies (scintillator SCSN-81 and the WLS fiber Y11) irradiated with electrons ($E \approx 4$ MeV). Our research has focused on the study of light collection from those assemblies.

The improvement in light collection is possible by reducing the size of the segment of scintillator. In this case, firstly, an impact of scintillation darkening is reduced because an average path of light from the place of its origin to WLS fibers becomes shorter, and secondly, the length of WLS fibers also becomes shorter, and hence the loss of light caused by its darkening is decreased. A dividing of tiles of the same tower into the equal number of segments allows keeping the existing geometric proportions. Each segment has own WLS fiber. WLS fibers from all segments of the tile are joined so that the total light of a tile will go through one clear fiber

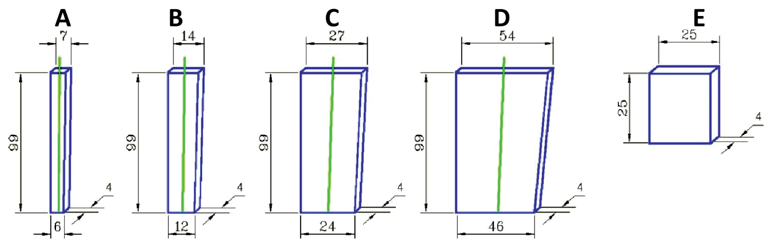

Fig. 6. Dimensions of some specific samples

to the optical connector of megatile. The widths of strips were defined as a half (D), a fourth (C), and one-eighth (B), one-sixteenth (A) from horizontal dimension of the main sample. WLS fiber in the strips is layed straight along a long side and mounted in the center of strip. Squares (E) have the dimensions 25×25 mm (Fig. 6). The last samples were needed for determination of a transmittance loss in the scintillators with different degrees of irradiation.

The numerous investigations during TDR preparation have shown that both scintillator and WLS fiber are able to ensure a normal operation of HE up to integral radiation level at 5 Mrad [6]. Our recent measurement of the main tile (see Fig. 5) irradiated with electrons to 5 Mrad is shown in Fig. 7, *a*. The relative light yield from the main tile is compared with old values presented in HCAL TDR for Cobalt-60 gamma source.

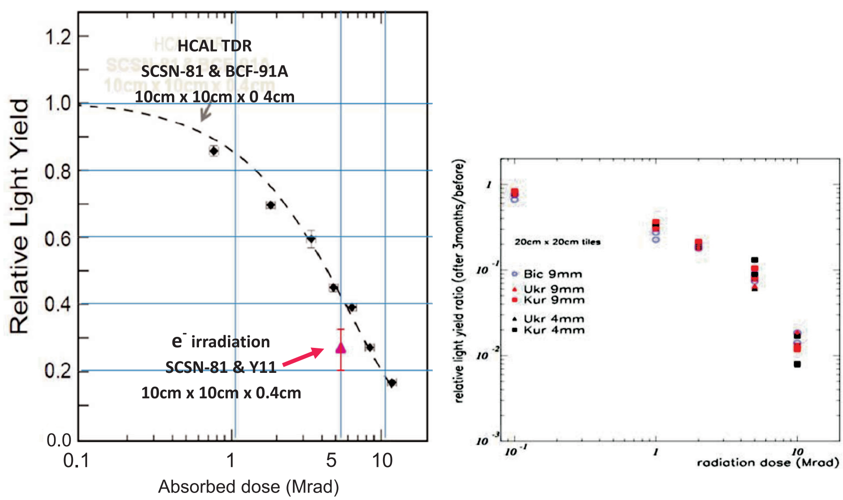

Fig. 7. *a*) The comparison of relative light yields of tile/fibre assemblies as a function of absorbed dose; *b*) light yield ratio, after radiation/before radiation for 20×20 cm, as a function of radiation dose, following 3 months annealing process

Our results are consistent with measurements shown in TDR. Figure 7, *b* shows relative light yield ratio of 20×20 cm tiles and Y-11 WLS fiber irradiated with Cobalt-60 source, after 3 months of annealing process [7]. In this measurement, the signal loss at dose of 0.1 Mrad is at the level of 10–15%.

Note that in both measurements, neutron damage is not included, as samples were only exposed to gamma source.

2. EVALUATION OF THE LIGHT COLLECTION IN STRIPPED TILE

A main goal of investigations described in the paper understands if a new method of light collection gives an advantage compared with current one. For that it is necessary to define the main parameters which cause a reduction of light during its propagation in the scintillator and in WLS fiber. A light yield from the different samples should depend on the quality of scintillator and WLS fiber, which depends on the degree of degradation of the scintillator and WLS fiber after absorbtion of a radiation dose D. A method how to combine several WLS fibers coming from one stripped tile is shown in Fig. 8. It can be assumed that the amplitude of the output light signal A(D) depends on the following factors:

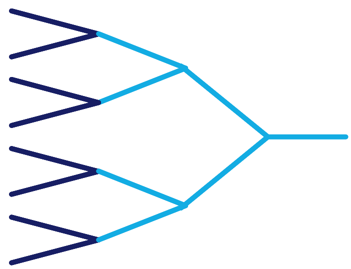

Fig. 8. The stages of “OR” connection

$$A(D) = S(W)\, k^N f_1(W/\lambda_{\text{sc}}(D))\, f_2(L/\lambda_{\text{WLS}}(D))\, J_{\text{sc}}(D)\, J_{\text{WLS}}(D), \quad (1)$$

where $S(W)$ — amplitude of the output light signal from strip of width W without irradiation; f_1 — attenuation factor which depends on strip of width W and attenuation length of scintillator $\lambda_{\text{sc}}(D)$ irradiated with a dose D; f_2 — attenuation factor which depends on mean length L of WLS fiber and attenuation length of WLS fiber $\lambda_{\text{WLS}}(D)$ irradiated with a dose D; $J_{\text{sc}}(D)$ — a relative light yield of scintillator irradiated with a dose D; $J_{\text{WLS}}(D)$ — a degradation level of WLS fiber irradiated with a dose D; k — transmittance loss in one “OR” connection; N — number of stages of “OR” connections.

3. EXPERIMENTAL RESULTS OF RADIATION TREATMENT OF SCINTILLATOR SAMPLES

The scintillator samples for investigation were defined (see Fig. 6). Ten copies of the sample of each type were prepared. The radiachromic dosimeters (special films with thickness 42.5 microns and dose range 0.05–20 Mrad) to measure a value of absorbed dose were used [8]. Several measurements were performed before irradiation of samples:

1. Primary check of a transparency of radiachromic dosimeters;
2. Measurement of the light yield of all samples. The measurement was carried out on the stand with a radioactive source of ^{90}Sr;
3. Measurement of a transmittance loss in samples. A stack from 6 samples is put on the photocathode of the photomultiplier and amplitude of signal is measured (see Fig. 9);
4. Measurement of a transmittance loss in WLS fibers.

Next steps of work were connected with irradiation of the prepared samples with electrons in the National Center for Particle and High Energy Physics (Minsk, Belarus):

1. Irradiation of scintillator samples (main, specific A/B/C/D/E) with electrons for accumulating of doses 0.5, 1, 5, 10 and 30 Mrad;
2. Evaluation of absorbed dose was determined for each sample separately by measuring of transparency of the radiachromic dosimeter then compared with dose measurement of on-site dosimetry services.

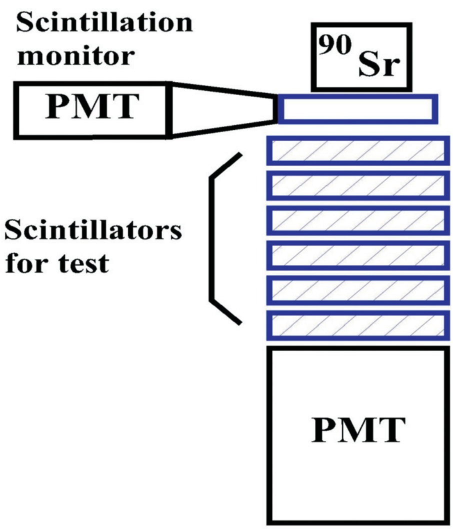

Fig. 9. Measurement of light attenuation factors for the scintillators

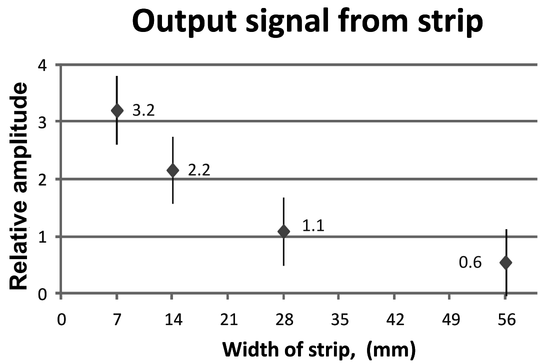

Fig. 10. Dependence of signal amplitude on sample width

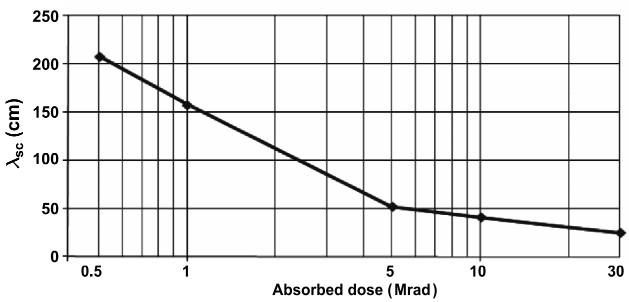

Fig. 11. Dependence of scintillator attenuation length λ_{sc} on absorbed dose

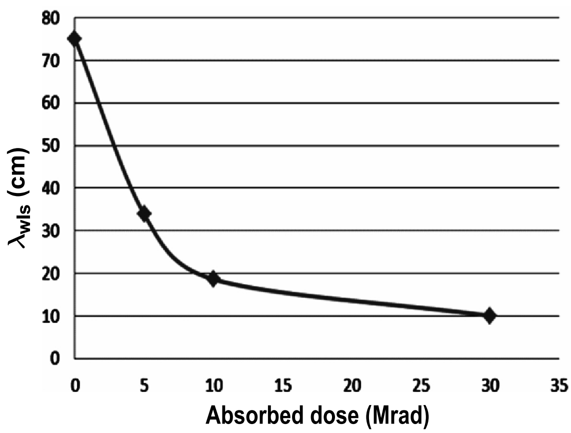

Fig. 12. Dependence of WLS fiber attenuation length λ_{WLS} on absorbed dose

Next steps of work were connected with the measurements of already irradiated samples:

1. Light yield measurements of all samples were carried out on the stand with a radioactive source of ^{90}Sr (see Fig. 10). Results were normalized to the signal from the tile (main sample) with the position of WLS fiber as in the real tile of HE;

2. Measurements of the transmittance losses in the scintillator and WLS fiber;

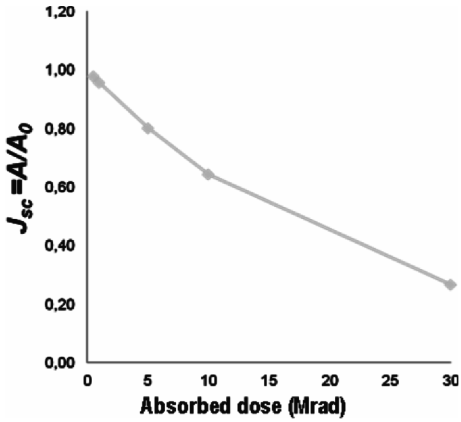

Fig. 13. Degradation factor of scintillator light yield J_{sc} vs. absorbed dose

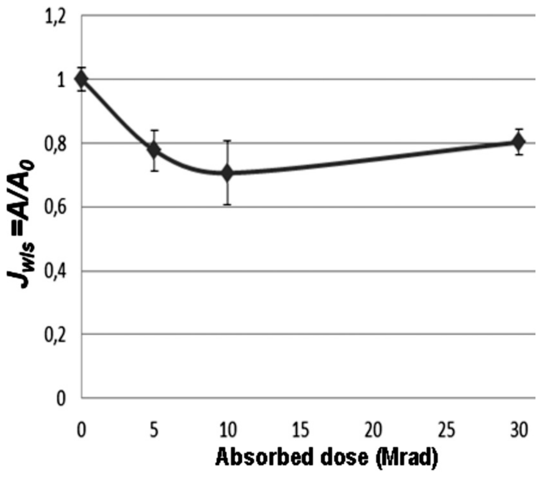

Fig. 14. Dependence of conversion efficiency of WLS fiber J_{WLS} on absorbed dose

3. Measurements were repeated daily for several days to determine the recovery time of scintillators and WLS fibers.

The results of measurements were analyzed and the attenuation lengths of scintillator $\lambda_{\rm sc}$ and WLS fiber $\lambda_{\rm WLS}$ in dependence on value of irradiation were obtained (see Figs. 11 and 12). The degradation factor of the scintillator light yield $J_{\rm sc}$ and the conversion efficiency of WLS fiber $J_{\rm WLS}$ were also defined (see Figs. 13 and 14).

4. INTRODUCTION OF OPTICAL "OR"

The original scheme of HE megatile uses one clear fiber for transmission of light from each tile to photo detector (see Fig. 15). It means a necessity to combine the light coming from several WLS fibers of tile's strips into one clear fiber. We propose to use optical "OR" coupler (see Fig. 16). It is used for light transfer from two fibers into one. Series connection of such couplers forms a tree structure. Each coupler of first stage is used for light transfer from two WLS fibers into one clear fiber. A coupler of the next stages is used for light transfer from two clear fibers into one clear fiber.

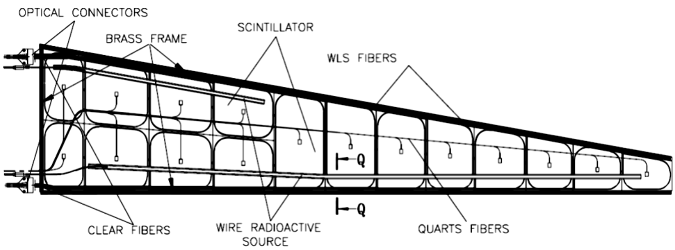

Fig. 15. A scheme of HE megatile

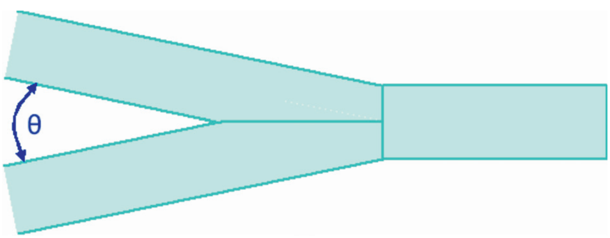

Fig. 16. A structure of optical "OR"

A number of primary WLS fibers ($n_{\rm WLS}$) is chosen in such a way as to ensure the equality $n_{\rm WLS} = 2^N$, where N is a number of consecutive stages of couplers. In this case, light from each input fiber will go to the

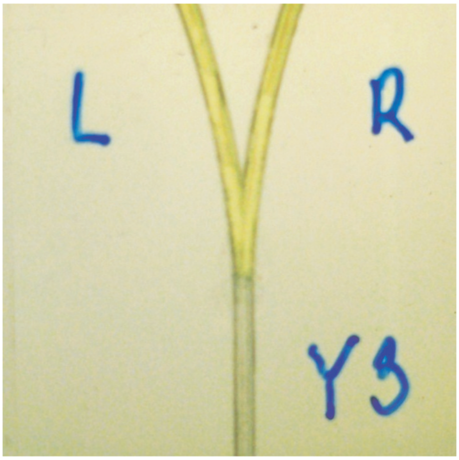

Fig. 17. A view of optical "OR"

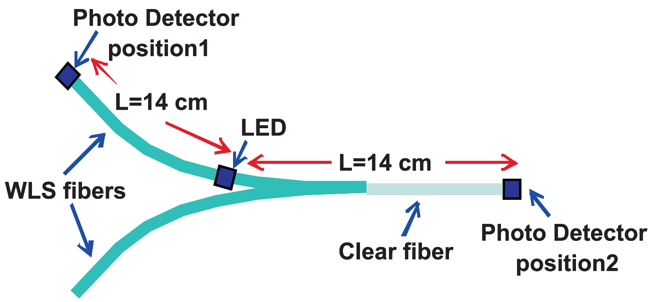

Fig. 18. The scheme for measurement of light loss in optical "OR"

output fiber with equal weight. A usage of optical "OR" couplers adds some extra loss of light. A factor k defines a loss of light in one coupler ($k < 1$). The optical "OR" coupler is formed by means of splice or cluing of two input fibers with one output fiber. Light losses will be minimal if the input fiber cores are cut at a slight angle and then polished and bonded to the polished end of the output fiber. Low excess light loss (1.9 dB at 660 nm wavelength) was demonstrated in Y-branching plastic optical waveguides [9]. Light losses will increase with an increase of angle θ between two input fibers.

The detail connection of three fibers is shown in Fig. 17. A blue LED was used to measure a loss of light in the optical "OR" (see Fig. 18). Light was measured by Photo Detector located on the end of fiber. The distances between LED and the Photo Detectors were the same. The factor k is defined as a ratio of signal amplitudes from the ends of clear and WLS fibers. Three samples of the optical "OR" were investigated. The best result of a light loss in the optical “OR” is $k \approx 0.7$. It is real to reach the value of $k \approx 0.8$.

5. EVALUATION OF IMPROVING THE LIGHT COLLECTION IN STRIPPED TILE

A ratio $G(D)$ of the amplitudes $A(D)$ of the upgraded and standard options with the equal value of the absorbed dose will provide information about positive $(G(D) > 1)$ or negative $(G(D) < 1)$ effect of the tile upgrade:

$$G(D) = \frac{A_u(D)}{A_s(D)} = \frac{S(W_u)\, k^N f_1(W_u/\lambda_{\rm sc}(D))\, f_2(L_u/\lambda_{\rm WLS}(D))}{S(W_s)\, f_1(W_s/\lambda_{\rm sc}(D))\, f_2(L_s/\lambda_{\rm WLS}(D))}, \quad (2)$$

where W_s — a width of main sample and a width of strip $W_u = W_s/2^N$; s — an index for variables of the main sample; u — an index for variables of strip.

The functions f_1 and f_2 may be represented as follows: $f_1 = \exp(-W/\lambda_{\rm sc})$; $f_2 = \exp(-L/\lambda_{\rm WLS})$. In this case a ratio $G(D)$ may be represented as:

$$G(D) = \frac{A_u(D)}{A_s(D)} = \frac{S(W_u)}{S(W_s)}\, k^N \exp\left[\frac{(2^N-1)}{2^N}\,\frac{W_s}{\lambda_{\rm sc}(D)} + \frac{L_s - L_u}{\lambda_{\rm WLS}(D)}\right]. \quad (3)$$

It should be noted that a ratio of $G(D)$ does not depend on the parameters $J_{\rm sc}(D)$ and $J_{\rm WLS}(D)$. The graphical view of the formula (3) is shown in Fig. 19.

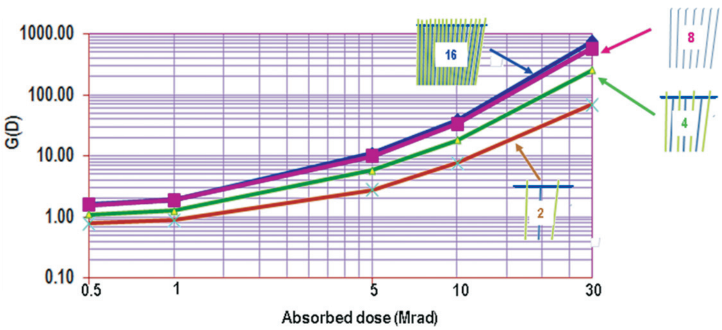

Fig. 19. Compare of light outputs of the upgraded and standard options with equal absorbed dose

A relative light yield from the experimental data was also found (see Fig. 20). Measurements of light yield for main sample and stripped sample (16 strips) were performed at the same conditions. The calculated results are given for two different values of a transmittance loss in

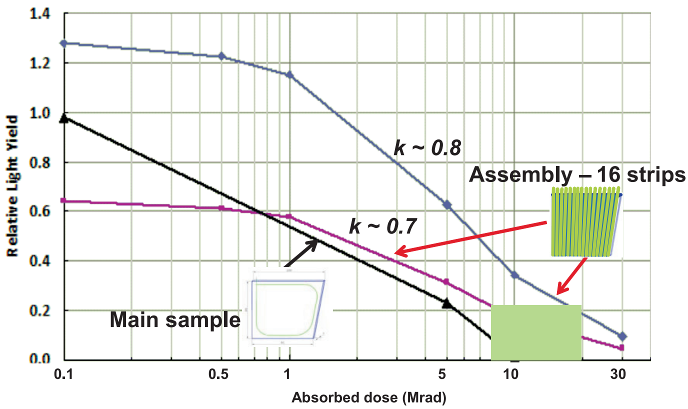

Fig. 20. Calculated results of light yields from different strips based on our measurements

one optical “OR” ($k \approx 0.7$ and $k \approx 0.8$). Light green area defines the possibility to increase the radiation hardness of most irradiated HE tiles up to 20 Mrad.

CONCLUSION

The final results are shown in Fig. 19. The ratio $G(D)$ of the amplitudes of the upgraded and standard options practically becomes positive ($G(D) > 1$) for all upgraded options.

Series of measurements on several assemblies of SCSN81 scintillator + Y-11 WLS fiber with electron beam were performed and a set of experimental results wwere obtained:

- Dependence of signal amplitude on the sample width.
- Transmittance loss in scintillator and its attenuation length in dependence on absorbed dose.
- Transmittance loss in WLS fiber and its attenuation length in dependence on absorbed dose.
- Degradation factor of scintillating ability in dependence on absorbed dose.
- Conversion efficiency of WLS fiber in dependence on absorbed dose.
- Possibility of combining several WLS fibers using the scheme of optical “OR”.
- Making several pieces of optical “OR” and measurement of transmittance loss in one optical “OR”.
- Compare of light outputs of the upgraded and standard options with equal absorbed dose.

It is shown that the proposed method will allow increasing the radiation hardness of most irradiated HE tiles up to 20 Mrad.

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