# STUDY OF THE DOSIMETRIC PROPERTIES OF $Al_2O_3$:C,Mg RADIOPHOTOLUMINESCENT (RPL) DETECTORS

ONUR MURAT

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# Table of contents

## Abstract

Aluminum oxide doped with carbon and magnesium ($Al_2O_3$:C,Mg ) was investigated to use together with immobilization masks used in radiotherapy treatments. In this way, thanks to RPL properties of the $Al_2O_3$:C,Mg the masks can be used for patient dosimetry after treatment sessions. Linearity, reproducibility, dose range and uniformity of the $Al_2O_3$:C,Mg material create challenges to use this powder in vivo dosimetry. The reading system is also studied to obtain higher sensitivity levels. Irradiated samples were read with Red and UV excitations. UV excitation with further optimized filter set up will be promising for future readings. The coating device can provide homogenous coating layer for samples. In 2D reading tests, reading protocol first optimized and height and surrounding effects were studied. In dosemaps and spatial resolution tests the maximum resolution with certain aperture was seen. Increasing resolution with smaller aperture can create problems for sensitivity.

# 1. Introduction

The internship takes a place in SCK-CEN (Belgian Nuclear Research Center) in Belgium in order to finalize the Master Nuclear Energy program Nuclear Plant Design option in ENSTA ParisTech at M2 year. The title of the project is "Study of the dosimetric properties of $Al_2O_3$:C,Mg radiophotoluminescent (RPL) detectors".

This study performed in the framework of a research project in Belgium Nuclear Research Center called DoseMask. Some concepts and definitions should be introduced before presenting the DoseMask project. This includes with the basics of radiological protection and external beam radiotherapy. After that the aspects of RPL dosimetry are also introduced.

In the materials and methods section the samples and reading systems after that tests and obtained results will be presented. Lastly, the conclusion of the results will take a place.

## *1.1 Ionizing Radiation*

Ionizing radiation is basically defined as radiation which has an energy level larger than the minimum energy necessary to ionize an atom. Alpha particles, Beta particles, neutrons, X and gamma rays are examples of ionizing radiation. Since the ionizing radiation has very short wavelength it can deposit large amount of energy in the exposed material. This energy could be very dangerous for living tissues as it can damage DNA inside cells and as a result cause cell death. In order to know the biological effects of ionizing radiation it is crucial to measure how much energy is deposited in the tissue being exposed.

## *1.2 Absorbed Dose*

Absorbed dose corresponds to energy absorbed per unit mass. The unit of absorbed dose is the gray (Gy) which equals to 1 Joule of absorbed energy in 1 Kilogram of tissue. Absorbed dose gives the measure of chemical or physical effects created by a given radiation exposure in an absorbing material. (*Lamarsh, 2001*)

## *1.3 External Beam Radiotherapy*

Radiotherapy (RT) uses ionizing radiation such as x-rays, gamma rays or electron beams to kill cancer cells. During the treatment the tumor should be exposed to very high doses of ionizing radiation while avoiding the exposure of healthy tissues. Accurate localization of the tumor, positioning of the patient and beam placement are therefore crucial, so immobilization of the patient becomes necessary. In order to immobilize the patient during treatment and between different treatment sessions personal immobilization devices are used. One of the these immobilization devices is the immobilization mask produced by ORFIT (see Figure 1) which is made of a thermoplastic material that can molded on the patient when it is warmed up.

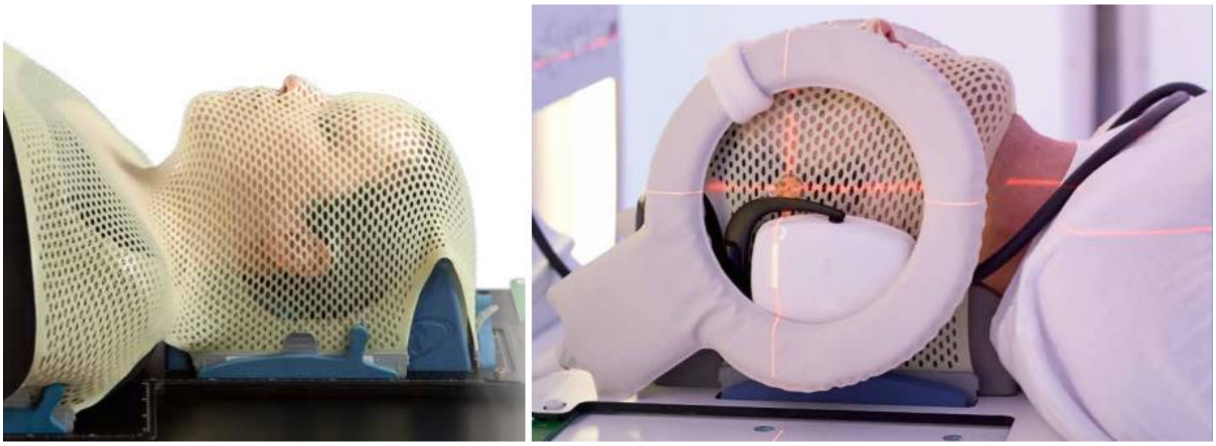


**Figure 1 - Immobilization Mask Produced by ORFIT**

In order to allow for a quality control of the RT treatment chain it is important to estimate the actual dose distribution delivered to the patient. The dose that is delivered to the patient needs to be known to be sure that correct amount of dose is received by the patient. Therefore in vivo dosimetry becomes an important part of quality assurance processing the radiotherapy treatment. In Vivo dosimetry can be performed by putting many small detectors on the patient's skin or inside natural cavities. However this is labor intensive work and it lacks of good reproducibility, so it is not done in every day clinical practice.

### *1.4 DoseMask Project*

The idea of the dosemask project is to create a radiotherapy immobilization mask with dosimetric properties that would allow routine in vivo dosimetry in radiotherapy. In order to create the dosemask, the dosimetric material can be added to the thermoplastic material of the mask or coated on top of the mask. Using an appropriate reading system the mask can be read after treatment sessions to estimate received dose by the skin of the patient. In this way the mask can be used as an immobilization device and at the same time as an in vivo dosimetry system.

### *1.5 Dosimetry*

TL (Thermoluminescence) and OSL (Optically Stimulated Luminescence) are the most widely used luminescence-based techniques used for personal and medical dosimetry. However, for the purpose of the dosemask these techniques are not convenient because dosimetric material based on TL requires to be warmed up to read its stored dosimetric information(incompatible with the thermoplastic behaviour of the mask), while OSL materials need to be kept in the dark because they are light sensitive(not practical to be used in the clinics). For this reason these techniques are not suitable for the DoseMask project. On the other hand radiophotoluminescence (RPL) have advantages over those two techniques: the signal stored in RPL materials can be read in a non-destructive fashion and these materials are not light sensitive. Thanks to these properties an RPL material could suit the needs of the DoseMask project.

### *1.6 Radiophotoluminescence Dosimetry*

Radiophotoluminescence is based on the optically active defects in the crystals. During the irradiation the charges in the valance band are ionized and they bounce to the conduction band. After relaxation of the charges they are trapped by the defects of the crystals. The number of electrons being trapped depends on the amount of the radiation received by the crystal, thus the dose absorbed by the crystal. Trapped charges can be excited with the stimulation light. Relaxation of the trapped charge after excitation results in the emission of a luminescence called radiophotoluminescence. The intensity of this luminescence is proportional to the amount of radiation absorbed by the crystal. Since the ionization of the trapped charges does not occur during the excitation, the reading of the RPL signal is non-destructive contrary to OSL. This allows reading the signal several times without destruction and, on the other hand, accumulating doses from different radiation exposures (For example; several RT treatment sessions).

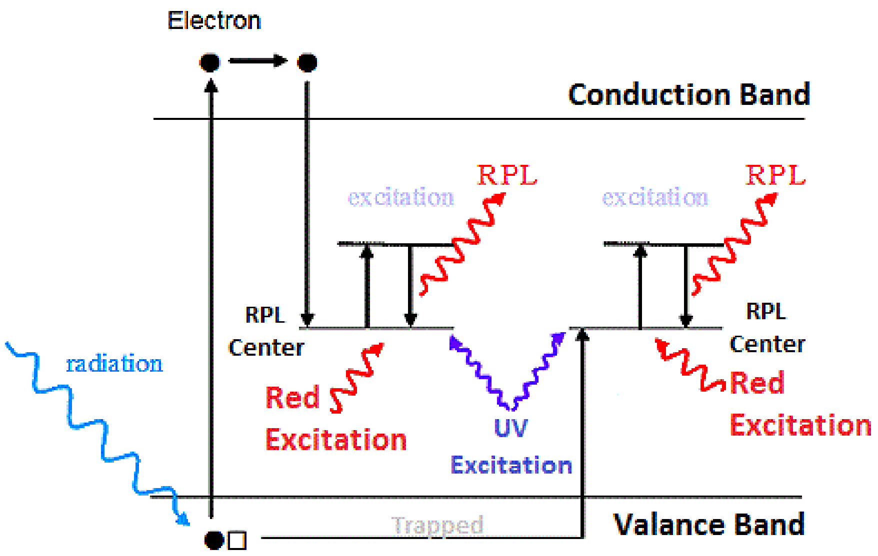



**Figure 2 – RPL process of the $Al_2O_3$:C,Mg. After irradiation electron is trapped by the specific RPL center of the material. Trapped charges can be excited by Red or UV lights and after that radiophotoluminescence is emitted during relaxation of the charges.**

Aluminum oxide doped with carbon and magnesium ($Al_2O_3$:C,Mg) is a ceramic material that shows RPL properties useful for personal and medical dosimetry. $Al_2O_3$:C,Mg was first introduced for optical data storage and is currently used as a fluorescent nuclear track detector in the dosimetry of neutrons, heavy charged particles and energetic protons. It is suggested also for RPL dosimetry. Crystals of the $Al_2O_3$:C,Mg were grown using the Czochralski crystal growth technique (*Akselrod, 2006*).

As grown $Al_2O_3$:C,Mg crystals contains high concentration of F and $F^+$ centers. During the crystal growth two $F^+$(Mg) centers compensated with $Mg^{2+}$ ions and $F_2^{2+}$(2 Mg) center is created. The new aggregate defect center has absorption at 435 nm and emission at 520 nm (Figure 3.a).

The electrons which is trapped in the defects can be produced using with 430 nm blue light two photon absorption.

$$F_2^{2+}(2Mg) + h\vartheta_1 \rightarrow F_2^{2+}(2Mg)^* \;\;,\;\; F_2^{2+}(2Mg)^* + h\vartheta_2 \rightarrow F_2^{3+}(2Mg) + e^-$$

Instead of 430 nm blue light these electrons can be produced by using ionizing radiation. Released electrons after ionizing radiation is captured by $F_2^{2+}$(2 Mg) defect centers and these centers transforms to the $F_2^{+}$(2 Mg) centers (Figure 3.b). In order to read the stored charges excitation at 335 nm and 620 nm results 750 nm luminescence emission (*Akselrod et al., 2003*).

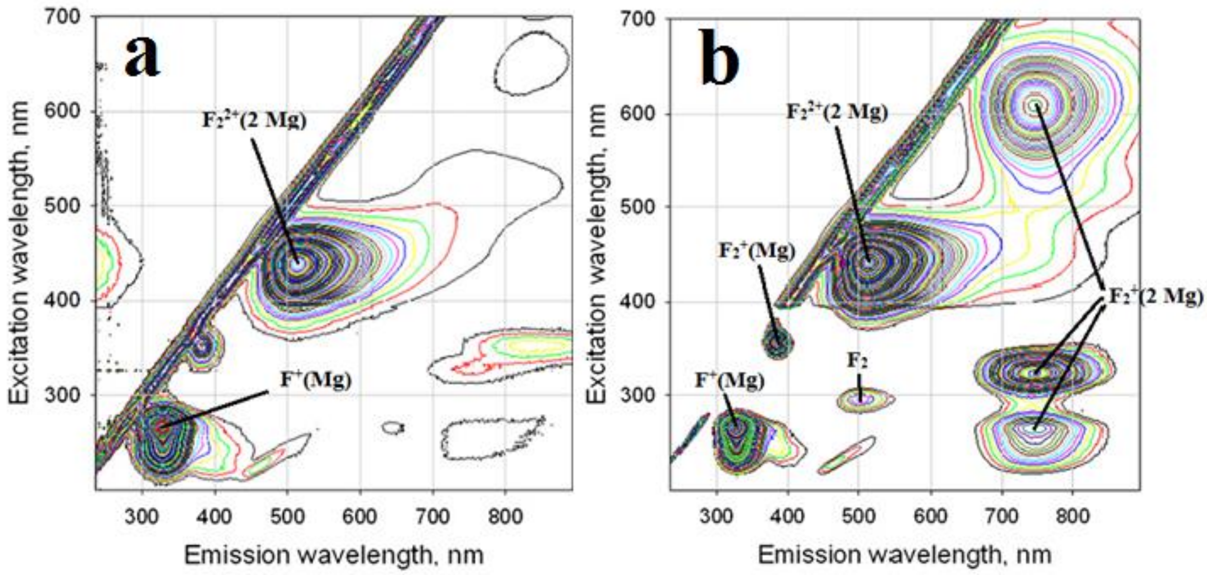



**Figure 3 - a-) Color centers of as-grown $Al_2O_3$:C,Mg, b-) color centers of $Al_2O_3$:C,Mg after irradiation. Before irradiation $F_2^{2+}$(2 Mg) center is excited with 435 nm wavelength light and this center emits 520 nm wavelength light. After irradiation new centers $F_2^{+}$(2 Mg) are formed. Excitation points of these new centers are 260 nm, 335 nm and 620 nm respectively. Emission wavelength of these centers is 750 nm.**

## 2. Objective

### *2.1 Challenges of DoseMask*

In order to make the dosemask applicable in radiotherapy dosimetry measurements should be reproducible, be able to map a large dose ranges and achieve high spatial resolution. This means that high sensitivity (50 mGy), linear dose response between 50 mGy and 60 Gy, uniform distribution of the dosımetrıc powder and spatial resolution less than 3 mm are needed.

### *2.2 Goals*

Ultimate goal of this project is to develop a radiotherapy immobilization mask for in vivo dosimetry following patient treatment. In order to achieve these conditions the following objectives which are based on challenges should be completed:

- Full characterization and optimization of the dosimetric properties of the RPL mask. This is performed by exploring for example: different concentrations of dosimetric powder, application methods and evaluating results of the RPL mask towards dosimetric films.
- Secondly, the reading system should be optimized to obtain high sensitivity with sufficient dose range and resolution. This is performed by using different stimulation light sources (UV, Red), optimizing filters sets and aperture openings.

## 3. Materials and Methods

### *3.1 RPL Detectors*

Two different types of RPL detectors are being tested in this phase of the project. Firstly, the thermoplastic (called Efficast) which is used in immobilization mask is coated manually with $Al_2O_3$:C,Mg powder in different concentrations (5%, 10%, 20%, 30%) (Figure 4, left and middle) and secondly RPL paper is tested which is a thin layer of $Al_2O_3$:C,Mg coated material (Figure 4, right). The RPL paper has thickness of 47 micrometer or 75 micrometer. The samples in the form of small discs (6 mm diameter) are obtained by punching the coated thermoplastic or the RPL paper.

If the efficast material and the RPL paper are not punched, they can also be used as 2D detectors (sheets) for performing measurements of the dose maps. Since the dosemask has 3D surface, in order to read the dose received by the mask 2D readings must be performed. Therefore, the samples and tests on 2D readings were performed.

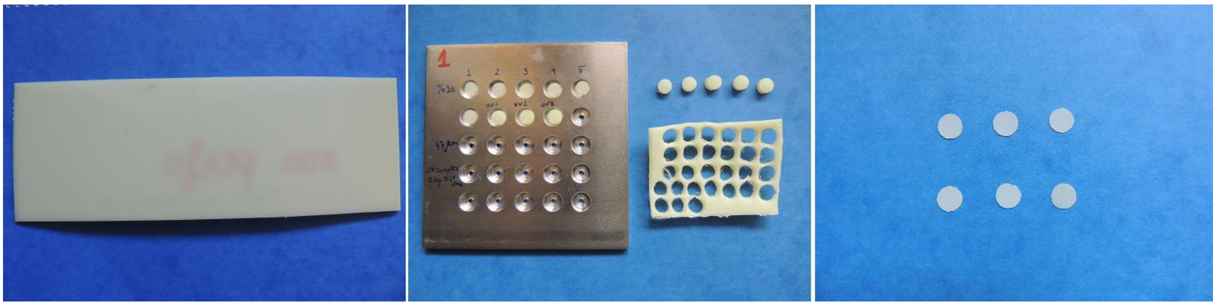


**Figure 4 - Efficast material before being coated (left), punched samples with $Al_2O_3$:C,Mg coating (middle) and punched RPL paper samples (right)**

### *3.2 Coating Device*

In order to make the homogenous coatings on the sample surfaces the coating device (Elcometer 3570, Figure 5) was used. Adjustment screw is set to desired coating thickness value and after that prepared coating material is put into reservoir. Coating is applied by sliding over the device on the surface.

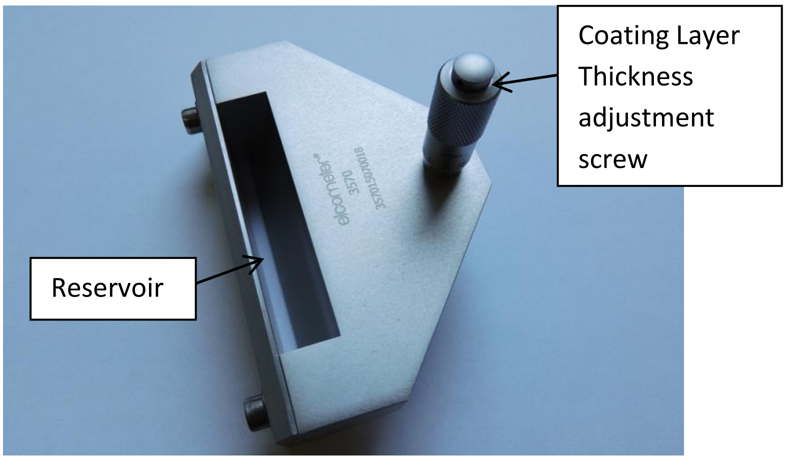



**Figure 5 - Coating Device produced by Elcometer**

In the 1D tests, the efficast was coated with using coating device. The thickness of the coating was set 100 µm and the percantage of the coating was 10%. For coating condition, the amount of dosimetric powder calculated from the weight of the chemicals. These chemicals are used to apply the coating on the surface and 10% coating represents that the dosimetric powder amount in the coating should be 10% of the weight of chemicals. In the case of mixing, dosimetric powder was added as much as 10% of the weight efficast plastic.

### *3.3 Irradiations*

The samples were irradiated with doses between 0 and 50 Gy. Two different radiation sources were used: the Riso TL/OSL reader and irradiator Co-60 gamma source. The irradiator of the Riso has a 1.48 GBq Sr-90/Y-90 beta source which emits beta particles at maximum energy of 2.27 MeV. The dose rate is approximately 80 mGy/s. The Co-60 gamma source was used to irradiate large samples.

### *3.4 Reading System*

The first reading system is Apollo 1D light tight box with a light detector on top and 4 LEDs pointing towards the sample (Figure 6, right).

The second reading system is used for 2D readings. An X-Y table provides movement of the 2D sample on the X-Y space. Movements provided by step motors produced by ZABER (Motorized Stage, 200 mm travel, RS-232 control). At the corner the reading hole with light detector on the top provides readings during X-Y table moving (Figure 6, left).

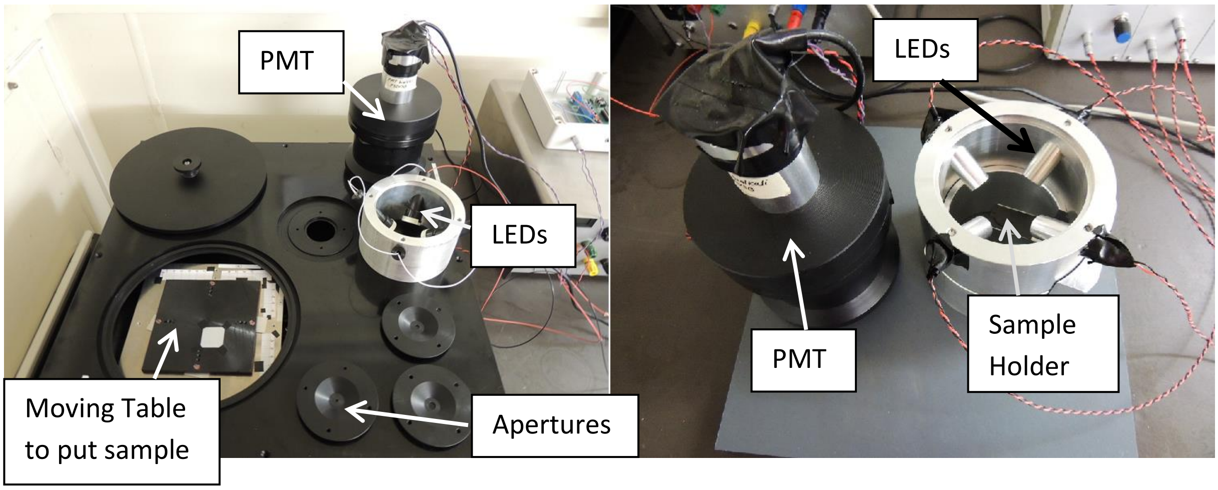



**Figure 6 - X-Y table and components (left), 1D apollo and components (right)**

The Red LEDs (Roithner LaserTechnik, ELJ-630-628, HighPower LED) and the UV LEDs (SETI Sensor Electronic Technology, Inc., UVTOP335) are used to stimulate the samples and read the RPL. Red LEDs has 630 nm peak wavelength while UV LEDs has 340 nm peak wavelength. Readings of the infrared (IR) light at 750 nm is carried out with Photo Multiplier Tube (PMT, Sens-Tech P30USB).

SP675 optical filters are used in front of the RED LEDs in order to prevent of passing higher wavelength of light and provide excitation of 620 nm absorption center of $F_2^+$(2 Mg) defect. The optical filters used in front of the PMT are Hoya B-370, RG-695 and SP800. These three filter performs a gap on wavelength and they let the fluorescence only fits this wavelength gap (Figure 7). Thus, only luminescence of the $F_2^+$(2 Mg) defect which is at 750 nm can reach the PMT, whereas other wavelengths are blocked by the these three filters.

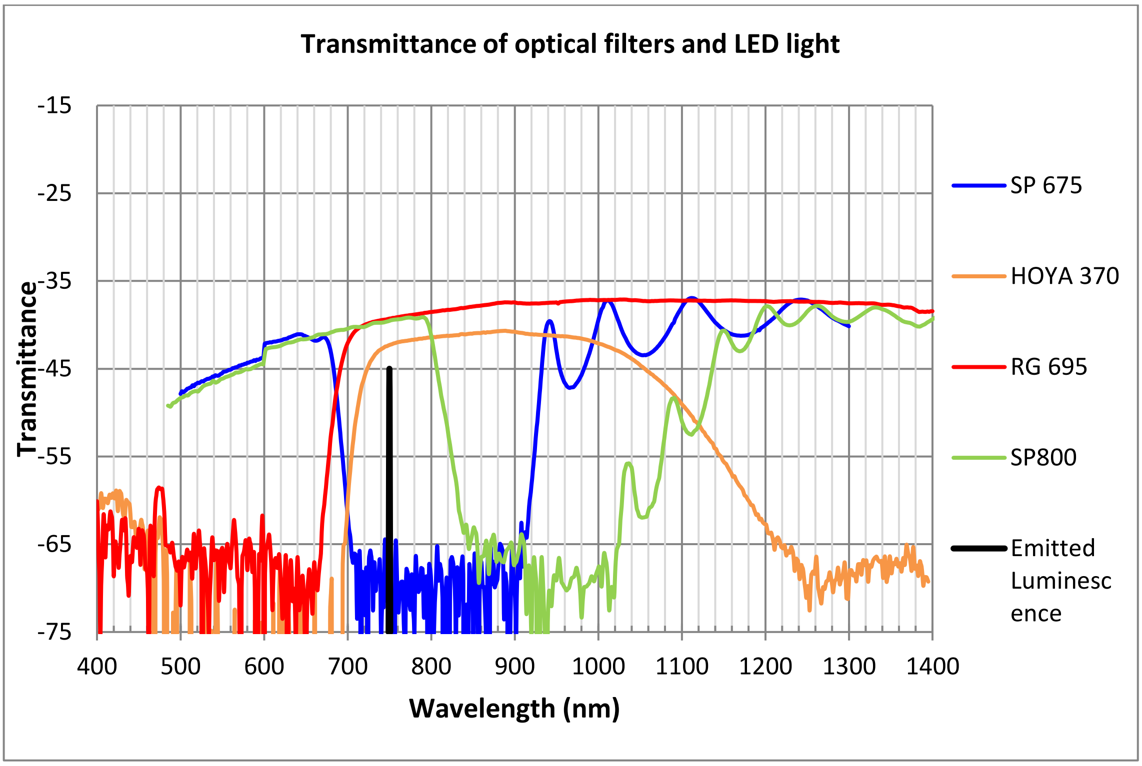



Figure 7 – Transmittance spectrum of optical filters

## 4. Results

### *4.1 1D Tests with Red LED*

In the beginning **reproducibility** tests were done using RPL paper sample. In different days with sample and without sample readings were done under the same readout conditions. Variation of the PMT counts were within ±3% for the 10 measurements.

**Sensitivity** is reflected in the slope of the background-subtracted RPL signal versus the dose curve. So the sensitivity is higher if a higher RPL signal is measured per unit dose.

**Linearity** of the response is reflected in the shape of the fitting. If all signal data can fit in a single line, then it shows a perfect linearity behavior. In order to check sensitivity and linearity of the system, the samples received cumulative doses and RPL signal was read after each irradiation. Firstly, all samples were read before irradiations to obtain 0 Gy signal. These 0 Gy readings are the background RPL signals. The backgrounds were subtracted from the RPL readings after irradiations to obtain absolute RPLs. These signals were plotted to check sensitivity and the linearity of the system (Figure 8).

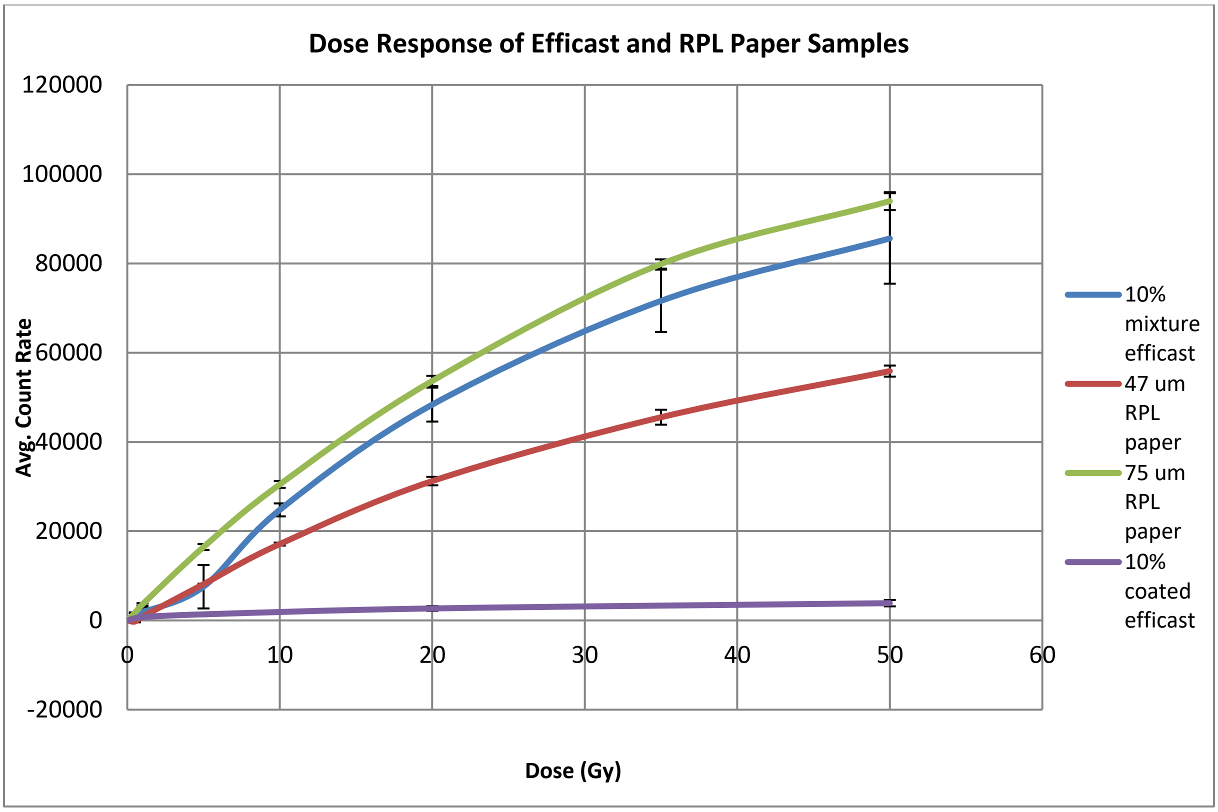



**Figure 8 - Dose Response of the 10% mixture efficast, RPL papers and 10% coated efficast in cumulative dose fashion. On the Y-axis RPL0-RPLx corresponds absolute RPL which background signal is subtracted. Count per second dimension is written as cps. On the X-axis dose levels are indicated in Gy dimension. Error bars corresponds to absolute standard deviation of the average RPL signal of set of samples. Each dose level points corresponds average RPL of 3 samples of 1D pellets. 4 Red LED and PMT is used for reading.**

The mixture of $Al_2O_3$:C,Mg on the efficast plastic samples is not distributed uniformly: in some regions the amount of powder is higher while in some regions it is less. This is why the RPL responses of the different samples with supposedly same concentration of powder are actually different from each other, which causes high variation on the dose points shown in Figure 10 (10% mixture sample error bars). 10% mixed samples show a higher variations of the RPL signals for each dose point compared to RPL paper. The percent standard deviations of the mixed samples were from 7.4% to 17.6% for different dose points. On the other hand for 47 µm paper the standard deviations were from 0.8% to 2.7%, for 75 µm paper they were from 0.2% to 1.5%. Inhomogeneity of the mixed samples causes this large variations on dose points. The standard deviation of the 10% coated samples was from 1.8% to 7.6%. The layer of the coated sample applied with coating device and it provides homogenous distribution of the powder compare to mixture efficast samples.

Results shows that all the four types of samples shows linearity until 10 Gy. After that RPL signal decreases per unit dose received. However, since the only RPL signals of 10 Gy and 5 Gy data points were obtained it cannot be assured that between these points linearity is sustained. 10% mixed sample and 75 µm paper samples shows similar sensitivities. Probably, the amount of $Al_2O_3$:C,Mg are close to each other while the 47 µm RPL paper has a thinner layer and thus it has less amount of $Al_2O_3$:C,Mg material. 10% coated material probably has the lowest amount of dosimetric powder among the samples. That's why it shows smallest sensitivity level.

Background levels of the RPL paper samples was around 30000 cps, for 10% mixed sample background level was around 34000 cps and for 10% coated sample was around 5500 cps. A high background level is not desirable for reading low dose levels. Samples which have high background level show higher absolute variations between them compared to samples with lower background level. When they are irradiated to low dose levels, separating the low dose level from the background signals becomes difficult. For example, samples with an average 50000 cps background level may show an absolute standard deviation of 1000 cps between them. If one of such samples is irradiated with an unknown low dose (e.g. 200 mGy), the absolute increase in the RPL may be near 1000 cps. Therefore, when trying to determine the dose level of that sample from the RPL counts, it is not possible to differentiate whether the measured signal is due to background or due to a low dose.

### *4.2 1D Tests with UV LED*

Previous works on Radiophotoluminescence properties of $Al_2O_3$:C,Mg crystals shows that UV stimulation could result in higher RPL signal (*S.A. Eller et al.,2013*). Therefore we also elaborated our reading system to allow UV stimulation.

A test was done using UV LEDs with same optical filters used in the Red stimulation set up. Results showed that the measured RPL signal for the 47 µm RPL paper samples irradiated with 50 Gy was not higher than the RPL signal obtained with Red stimulation set up. Therefore it was decided to optimize the optical filters of UV set up in order to increase its sensitivity.

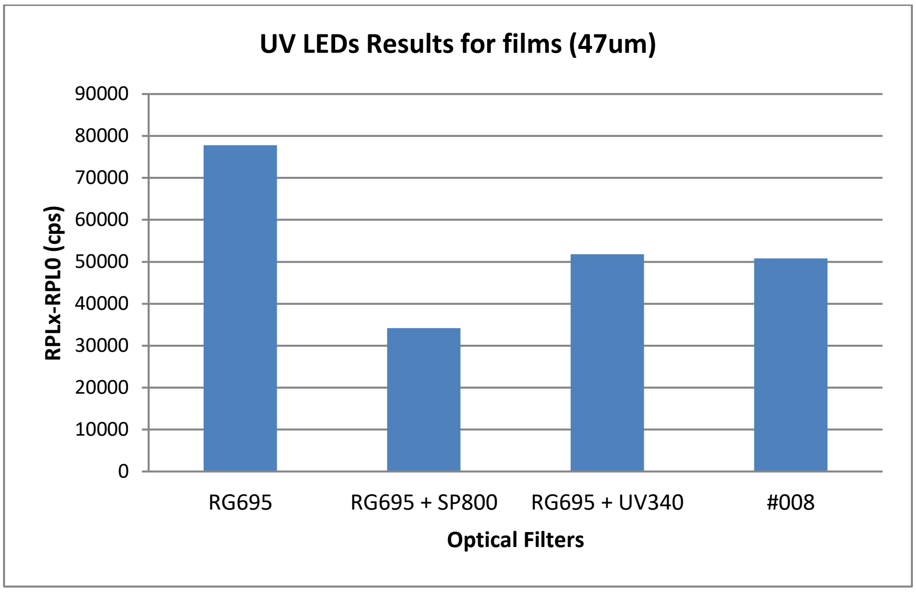



**Figure 9 - RPL paper dose response with UV stimulation after exposure to 50 Gy. 4 UV LED were used for excitation and PMT was used for reading. Only one 47µm RPL paper 1D punched sample was used.**

50 Gy irradiated 47 micrometer RPL paper is used for testing different combination of filters. Figure 9 shows that highest RPL signal is obtained when using the RG695 filter. In the Red stimulation the obtained background subtracted RPL signal was around 55000 cps (see Figure 8, 50 Gy dose point of 47 µm RPL paper), while with UV and RG695 the PMT counts reached around 78000 cps (see Figure 9). Results show that highest sensitivity is obtained with only RG695 set up in UV test. UV excitation with RG695 filter set up could be better alternative than Red excitation in dosemask based on higher sensitivity level.

However the background level was RG695 set up was around 37000 cps which is higher than the case of Red LEDs excitation. The background levels for 10% mixture was 34000 cps, for RPL paper 30000 cps and 5500 cps for 10% coated efficast in Red LEDs excitation.

### *4.3 1D Tests of Coated Samples with UV, Red LEDs*

10% coated samples prepared for 1D readings excited with UV and tests were performed with PMT.

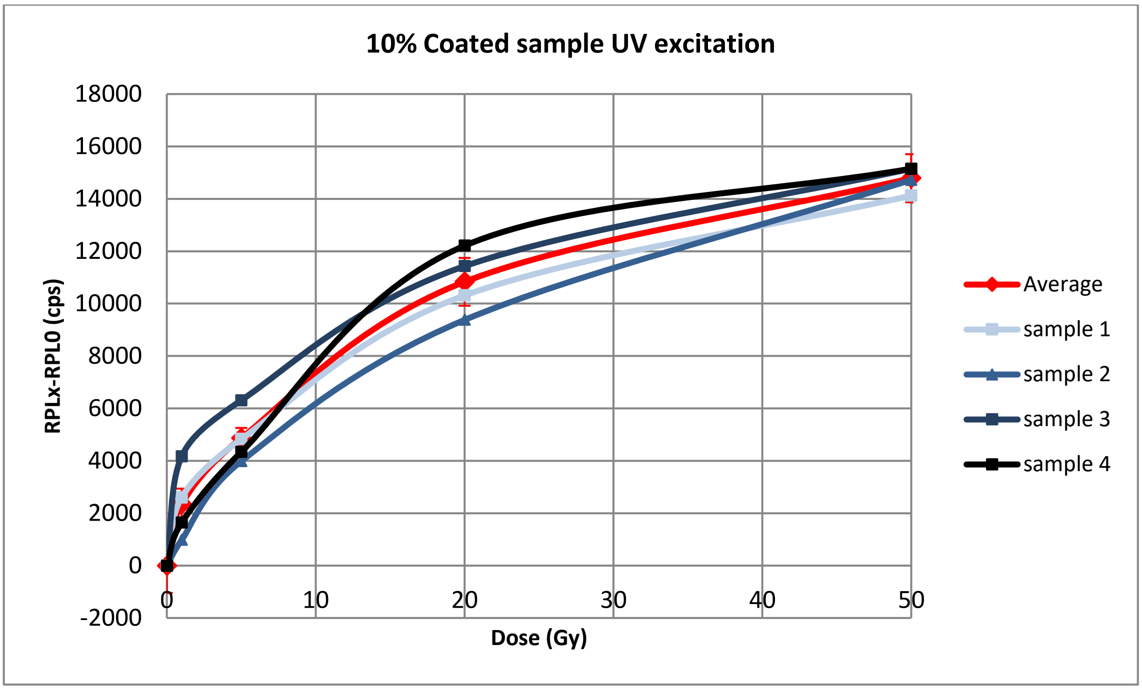



**Figure 10 - In the UV excitation case only RG695 optical filter was used.4 different samples were used.**

The background levels of the samples was around 30000 cps. The sensitivity of the UV excitation is much lower than the results of RPL paper and mixture with Red excitation. It is probably, total amount of dosimetric powder per unit area is not enough to create this level of sensitivity. Thicker coating layer or the increased percentage of coating can provide higher sensitivity.

The stretching and molding process will be performed on the patient faces before treatment session. That's why the effects on the coating needs to be studied. Stretch test was performed with 10% coated sample. The piece of coated sample was put into 70 ºC water for 3 minutes and it was stretched from the edges. In the beginning sample was 13 cm long and after stretching it became 20 cm long (65 % stretching was performed). The samples were taken from the stretched efficast for 1D readings.

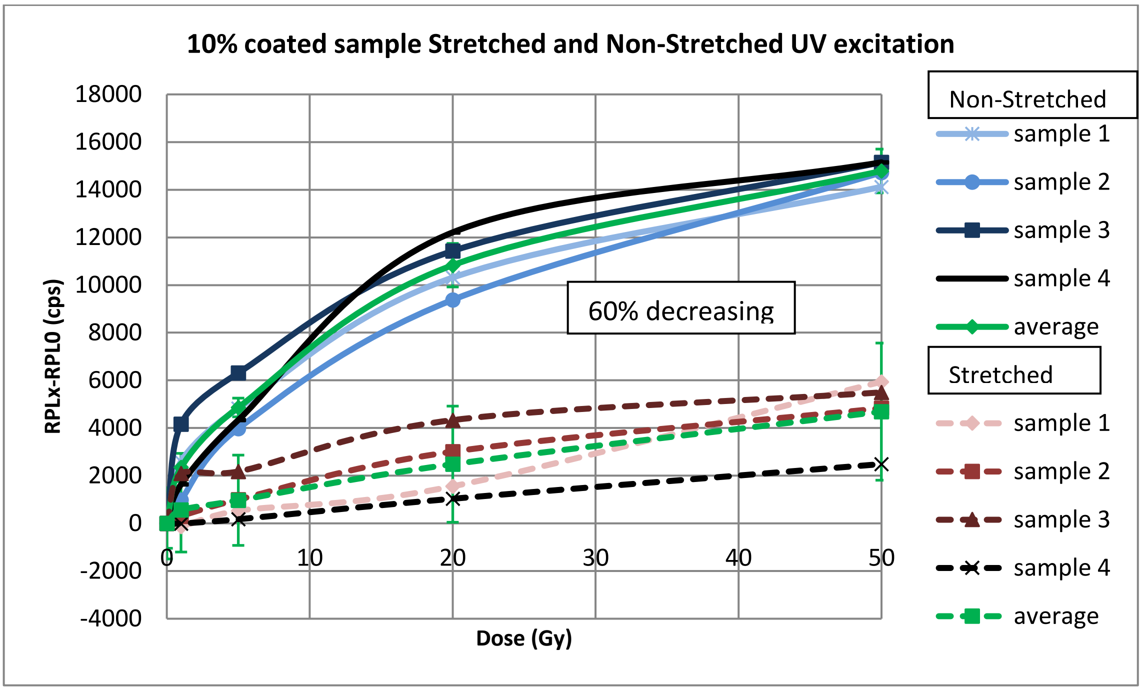



**Figure 11 - Readings were performed with UV excitation. In the UV excitation case only RG695 optical filter was used. 4 samples were taken before and after stretching.**

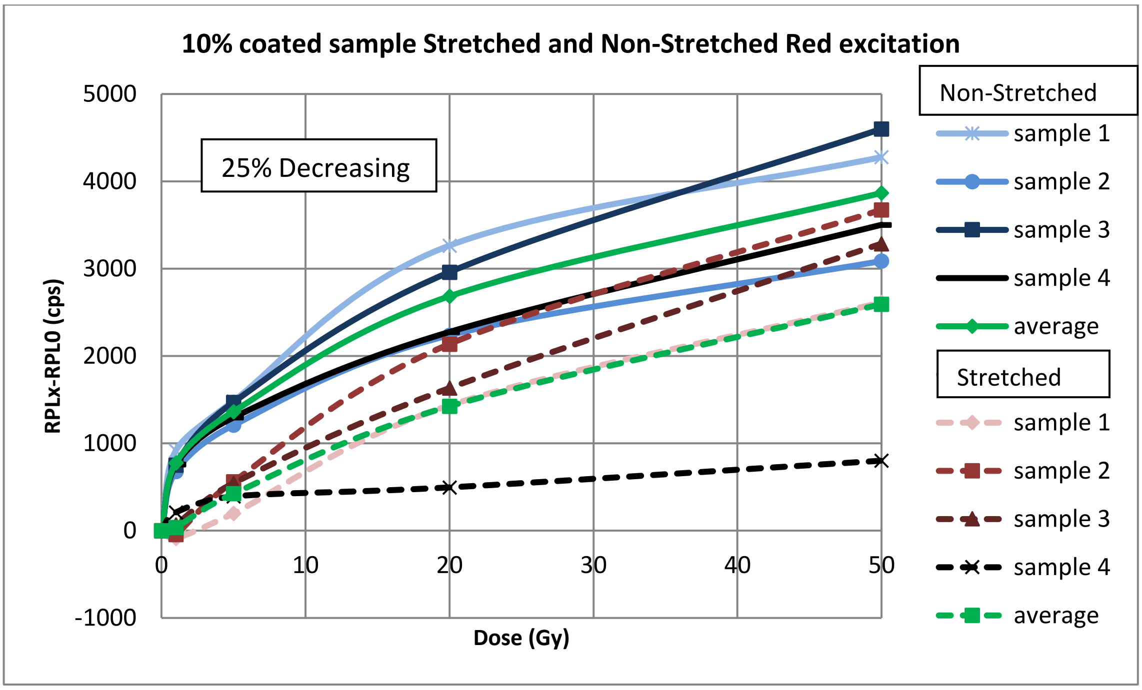



**Figure 12 - Readings were performed with Red excitation. 4 samples were taken before and after stretching.**

Results shows that for the UV excitation case count rates on dose points decreases around 60% and Red excitation case it is 25%. The process of the stretching apparently decreases the sensitivity of the samples. During the heating up the material in hot water it was observed that dosimetric powder interfere in the water and an amount of powder was lost. Also during the stretching amount of powder on the per unit surface area was reduced since the total area was increased. All these actions decreases the amount of powder on the surface and sensitivity.

The variation of the samples on dose points are higher than the test with 10% coating non-stretched samples. After stretching new distribution of powder over the surface was not homogenous as before anymore since the during the heating up process, losing the powder in water was not controllable action and during the stretching edges of the material was not equally pulled by two hand. That's why between samples high amount of variation was observed. In UV excitation results minimum 5% standard deviation on 1 Gy point and maximum 7.4% standard deviation on 50 Gy point was observed. In Red excitation results minimum 5.1% standard deviation on 1 Gy point and 18.9% standard deviation on 50 Gy point was observed. In each excitation case 4th samples were taken from very edge of a bending point. For this reason the 4th samples are little bit thinner than others and they showed some extreme cases on results.

Results showed that in each excitation case sensitivity decreases dramatically. In order to prevent loss of powder on the surface a protective layer could be coated.

### *4.4 2D Tests*

To go towards the ultimate goal to read the dose from an immobilization mask, the next step is to test and read RPL in 2D. Therefore, efficast plastic sample and RPL film sheets were used. In this 2D system the sample moves underneath the PMT and RPL was read from different positions on the sheets and plates. First tests were related to the time the PMT needs to measure RPL. Firstly, reading protocol was optimized. Also reproducibility of the reading systems was checked using a RPL film sheet. After that tests on the height of the XY table and what was the influence on the RPL signal was performed. Finally, reading 2D dosemaps started and have a measure of the spatial resolution of the system.

#### *4.4.1 Time Test*

Two RPL film samples was prepared each one of them 4.5 $cm^2$ size was cut and one of them was irradiated with 30 Gy and the other was not irradiated. Then they were placed together next to each other to make a larger 2D sample 9 $cm^2$, it represents an ideal dose/no-dose boundary (30 Gy and 0 Gy). This large sample was read in the 2D reader using with two different apertures (3 mm and 5 mm). Measurements were taken at the different points along the path that goes from non-irradiated paper to irradiated paper. For each position a total of 250 measurements of 20 ms each were performed (On each point PMT measured the RPL signal for 5 seconds). In order to find out the optimum reading time averages of the reading values were taken cumulatively. For instance, average of the first 10 reading datas created the value of the 200 ms reading at that point, with 100 data 2 second average value was calculated.

After that, for each reading time the transition section was checked between samples in order to find appropriate one. Also the standard deviation of the different measuring times were checked. The behavior of the measuring times which more than 1 second seems appropriate for reading in the result of 5 mm aperture. They do not have huge count variations as large as smaller reading time. Standard deviation of the average RPL signal stabilizes after 1 second of integrated measuring time (Figure 14). As a result, by considering the margins the measuring time was decided as 1.5 second. In the results of 3 mm aperture standard deviation behavior was same as result of 5 mm aperture. Measurement time 1.5 second fits for 3 mm aperture also.

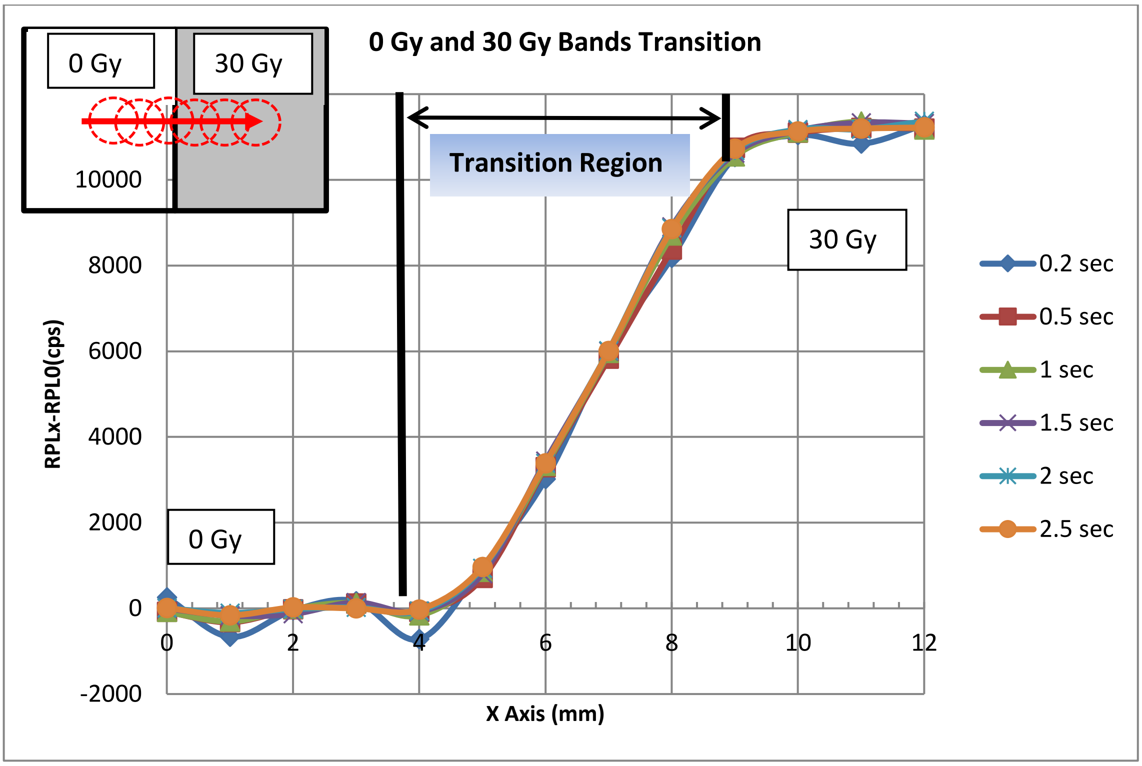



Figure 13 – For 5 mm aperture average counts on the reading pattern

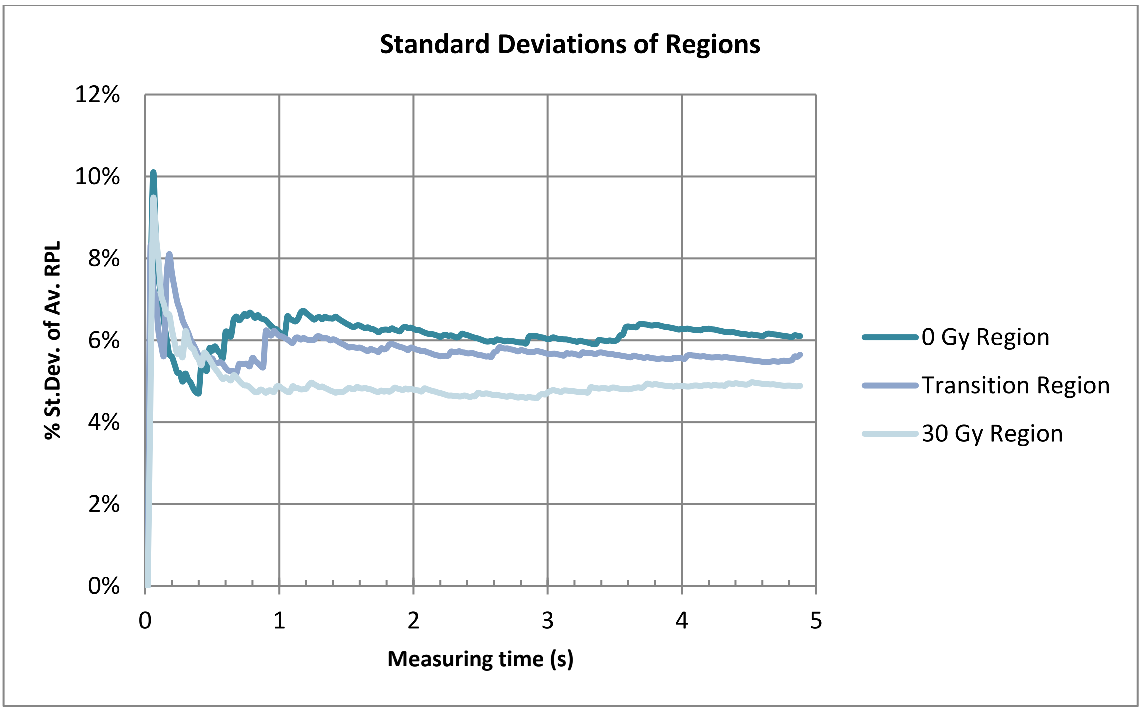
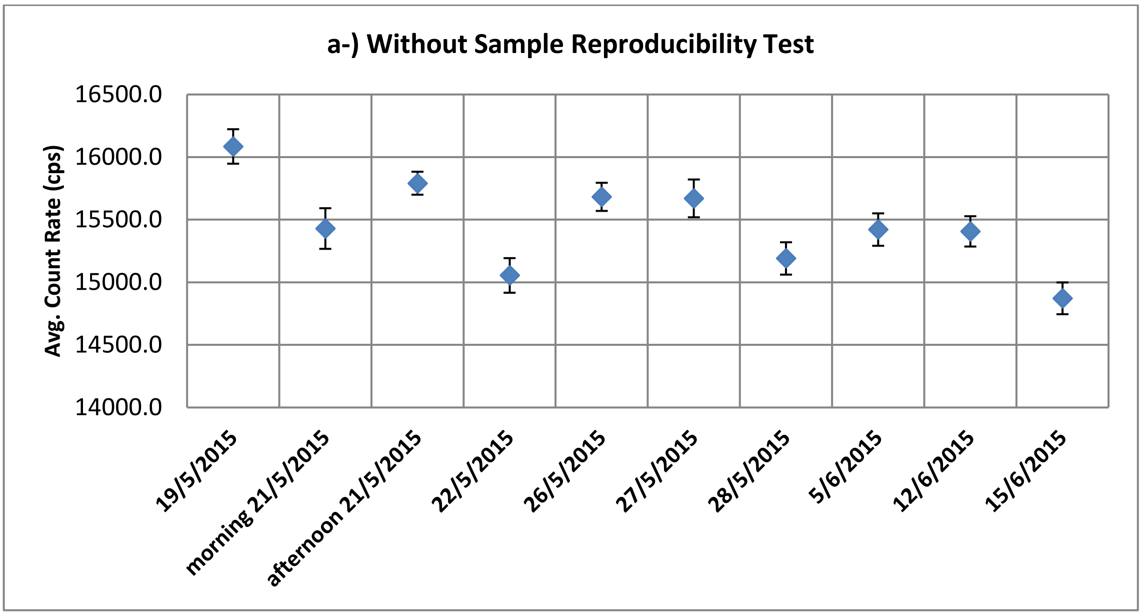



Figure 14 - Standard Deviations of 0 Gy region, transition region and 30 Gy region over the measuring time. 5mm aperture was used.

### *4.4.2 Reproducibility of 2D System*

Stability of the system was tested without any sample and with using non-irradiated RPL sheets. Tests were done on the different days to see the how system change and respond over time (Figure 14). In the result of with RPL paper and without sample the difference between highest count rate of the test and lowest one is around 5-6 percent.

For example, within the same day (on 21/5/2015) the signal is changed with 4.2% for without sample case and 5.6% for with sample case. Therefore stability of the system needs to be considered. The result of reproducibility test shows that system response is not the same on different days. The temperature fluctuations affects the sensitivity of the PMT, also output of the red LEDs can influence the RPL signal received.



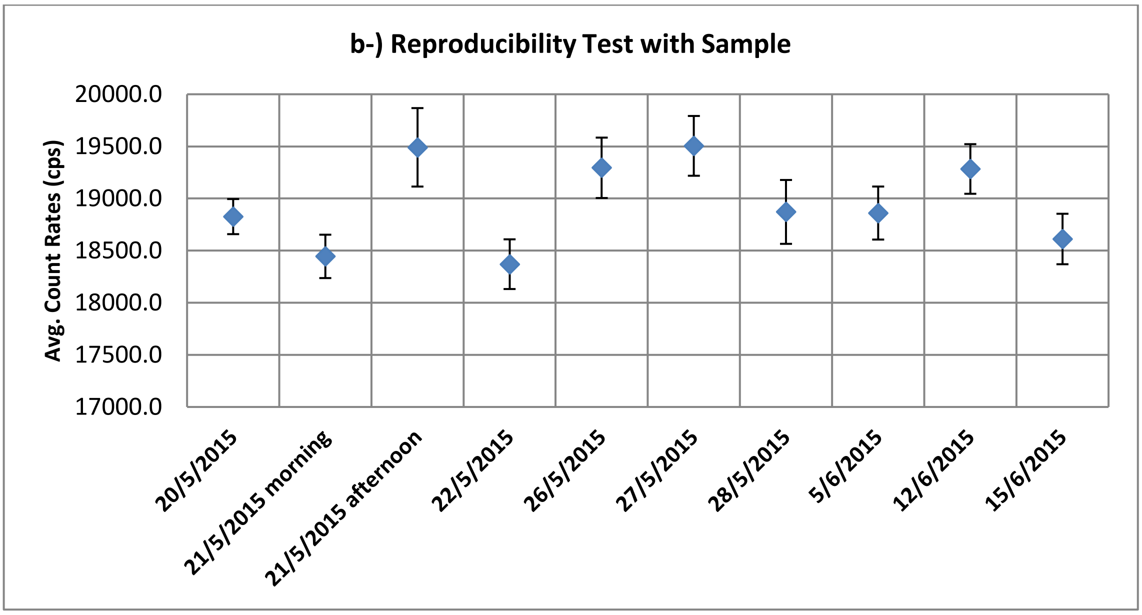




**Figure 15 - Reproducibility test results for different days a-) without any sample b-) with non-irradiated RPL paper**

### *4.4.3 Effect of Sample's Height*

The height of the sample in the 2D system may be varied and when the distance between the sample and PMT is changed sensitivity differs. For this reason series of tests with different distances were performed. Two samples of RPL paper were used: one of them was irradiated with 30 Gy and the other one did not receive any dose. Red LEDs and 5 mm aperture were used with PMT.

In Figure 16 the the count rates was shown in normalized based on values on 2.2 mm point in each sample. The count rate values of 0 Gy and 30 Gy samples at 2.2 mm point were 16616.05 cps and 37118.19 cps respectively.

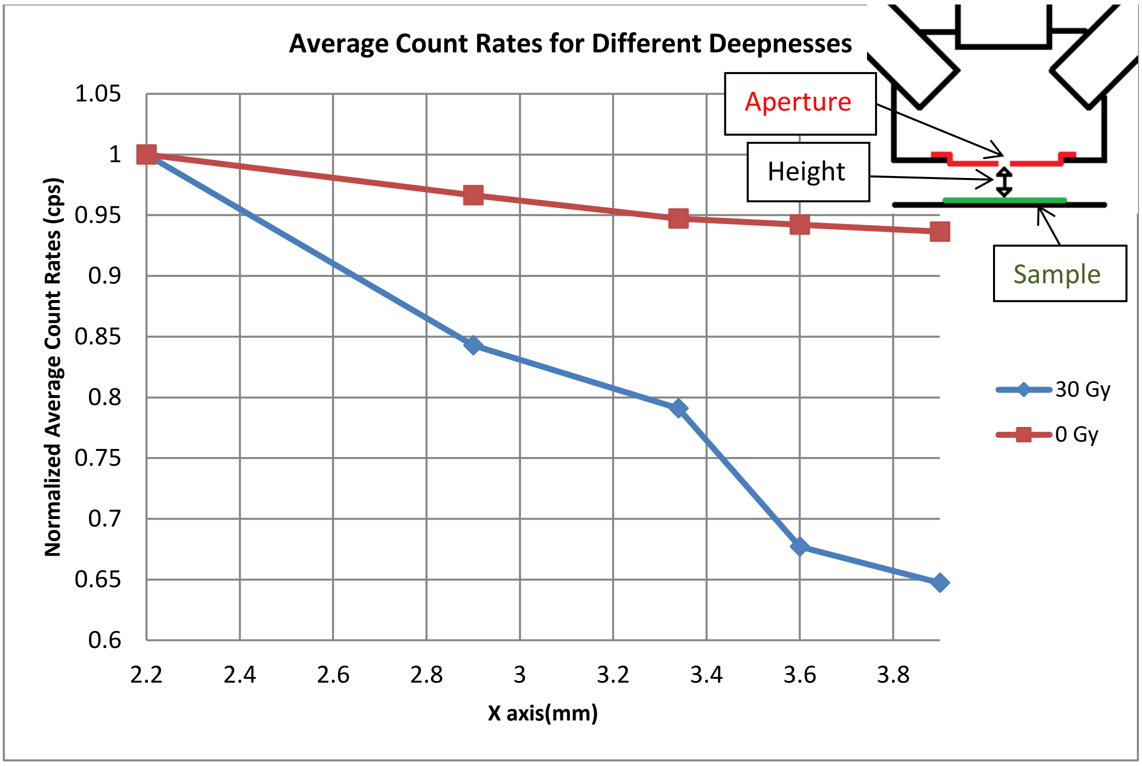



**Figure 16 - Average count rates of different height sizes between sample and aperture opening. X axis correponds the different heights between sample surface and aperture entrace which they were 2.2 mm, 2.9 mm, 3.34 mm, 3.6 mm, 3.9 mm respectively.**

The closest distances to the PMT were 2.2 mm and 2.9 mm. When count rates were checked of these points (2.2 mm and 2.9 mm) for the 0 Gy sample, the difference between them was %3.36. The difference is much higher for the 30 Gy sample case which was %15.72. This percentages was provided only for 0.7 mm height difference which is significantly important.

During the test samples should be close as possible to the PMT in order to get more counts and this way increase sensitivity. Even for a very small variations which is less than 1 mm can cause very large RPL signal differences. That's why during the tests height always must be fixed.

### *4.4.4 Dose maps*

In order to create a dose map 30% coated sample and RPL paper sample was used. Different size of stripes were cut and marked ones (Figure 17) were irradiated. Width of irradiated bands are 10 mm, 7.5 mm, 5 mm, 2.5 mm and 15 mm respectively. Irradiations were performed to obtain 5 Gy, 10 Gy and 30 Gy cumulatively. After each irradiation samples were read in 2D X-Y table using 5 mm aperture and PMT with Red excitation.

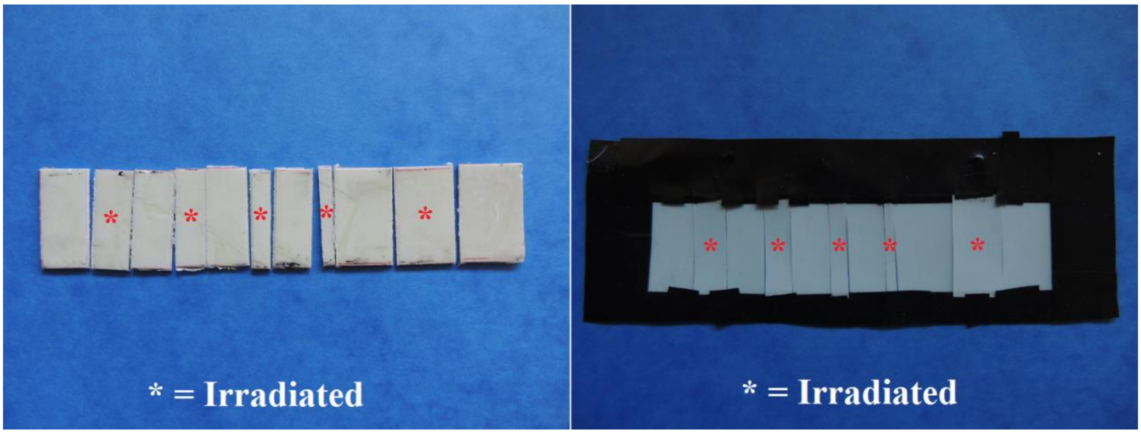



Figure 17- 30% coated efficast samples (left), RPL film sheets (right)

First of all, for the coated sample already shows a large variation and suggesting already that the coating was not homogenously distributed over the sample. Coating was not performed with coating device. The result of the coated sample was not appropriate for examining.

In the result of RPL paper for different dose levels (Figure 18) shows a better result than the efficast results. The RPL peaks are located in the same positions of the irradiated stripes. From 15 mm to 2.5 mm irradiated stripe the peak values of the regions decreased. The highest RPL peak was obtained for 15 mm thick stripe, while the lowest value was obtained for 2.5 mm thick stripe. For an irradiated stripe thickness lower than 5 mm, during the reading the 5 mm aperture also covers part of the area of the non-irradiated stripes. However when the width of the stripe increases (7.5, 10 and 15 mm) the peak value keeps increasing also. This indicates that aperture also captures the luminescence from the surroundings of the ideal visible area (aperture size).

To be able to distinguish the irradiated bands full width half maximum values of the peaks were determined. It seems that irradiated stripes can be distinguished up to a thickness of 5 mm. However for the real spatial resolution test the samples needs to be prepared with same width both irradiated and non-irradiated ones.

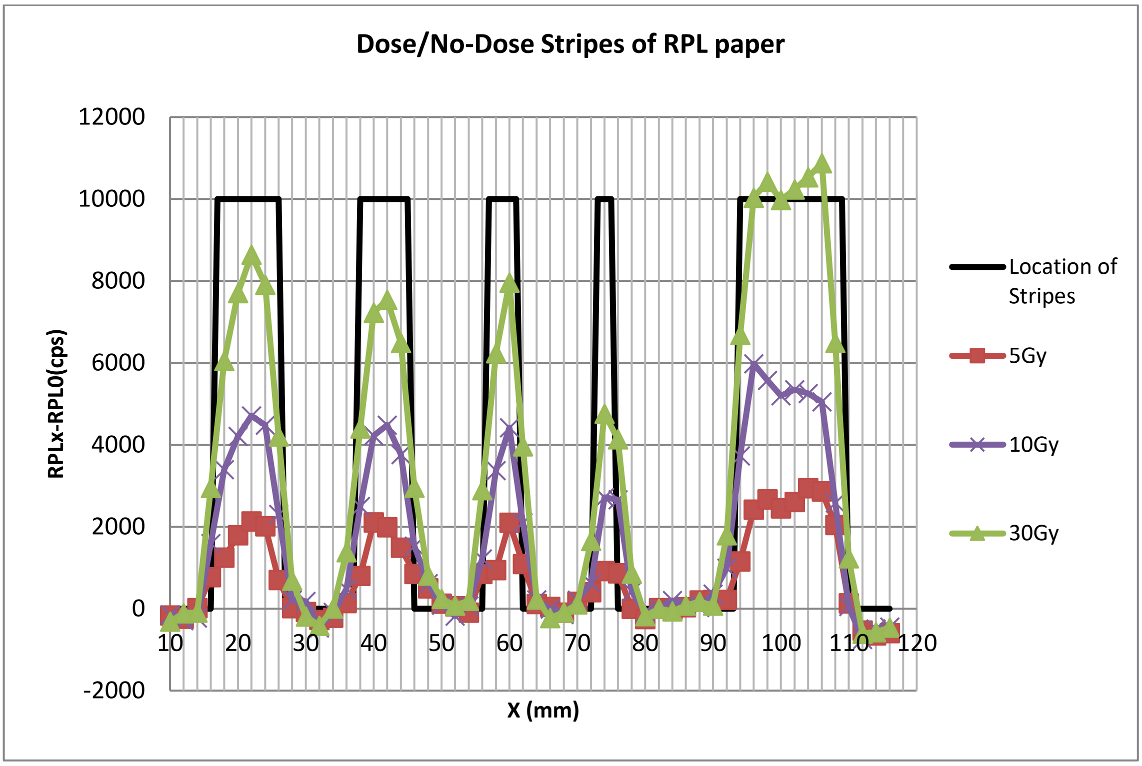
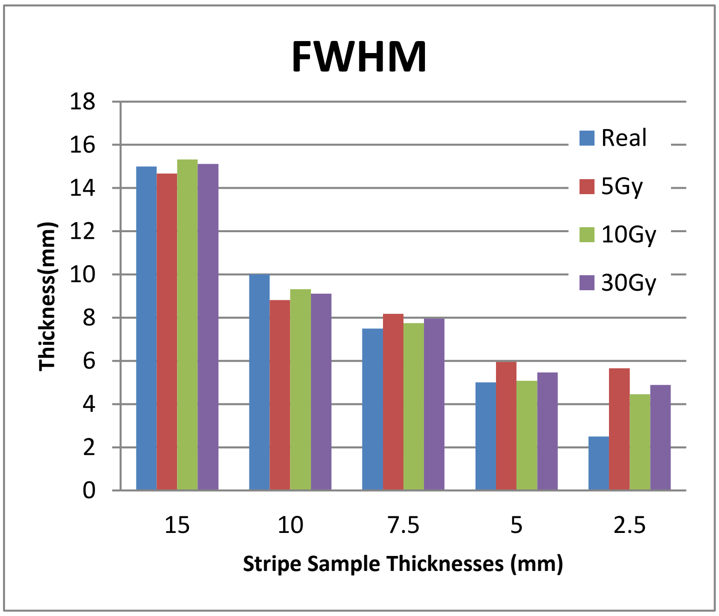



**Figure 18 – Dose response map of the RPL paper stripe group for 5 Gy, 10 Gy and 30 Gy. Location of stripes marked on the plot as reference. The count rate of the location of stripes plot is just for representing, it does not show a ideal case.**




| | FWHM (mm) | | |
|---|---|---|---|
| **Real Thickness (mm)** | **5Gy** | **10Gy** | **30Gy** |
| **2.5** | 5.66 | 4.45 | 4.88 |
| **5** | 5.96 | 5.08 | 5.45 |
| **7.5** | 8.18 | 7.74 | 7.95 |
| **10** | 8.82 | 9.32 | 9.11 |
| **15** | 14.67 | 15.32 | 15.12 |

**Figure 19 – Full width half maximum values of each stripe for 5 Gy , 10 Gy and 30 Gy**

### *4.4.5 Influence of Sample's Surroundings*

In the results of dose maps test it was observed that during the 2D measurement irradiated sample surfaces which have larger surface areas than aperture opening area can result in higher RPL signal values probably because of RPL signal coming from the surroundings of the ideal visible area.

In order to study of this effect 2D RPL paper was used with black papers punched with different sizes. Diameters of punched circles on the black paper were from 3 mm to 12 mm (3 mm, 4 mm, 5 mm, 6 mm, 8 mm, 9.6 mm, 12 mm) (Figure 19).

Firstly, RPL paper was read without black paper to see maximum RPL signal. After that the black papers with a hole in the middle were put on the sample to create dark surroundings of different sizes. Background levels were read and sample was irradiated to 10 Gy. 2D reading process was performed with 3 mm, 5mm and 7 mm aperture. Red LEDs and PMT were used for reading.

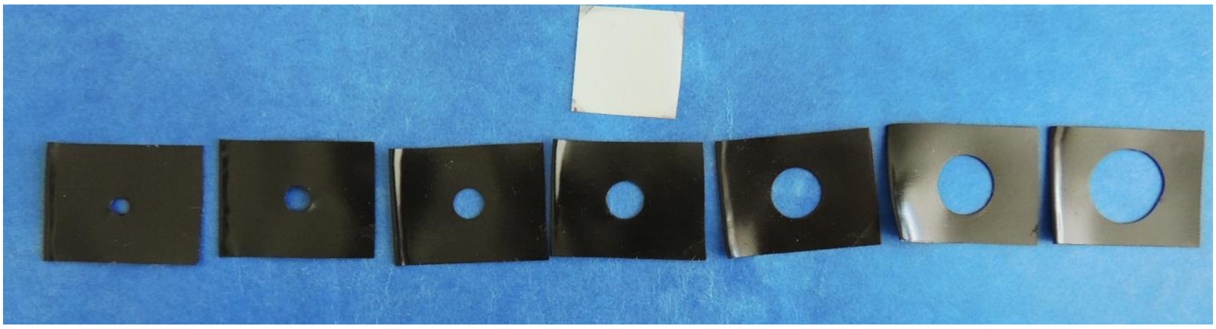


**Figure 20 – RPL paper sample and the black papers with different size of holes**

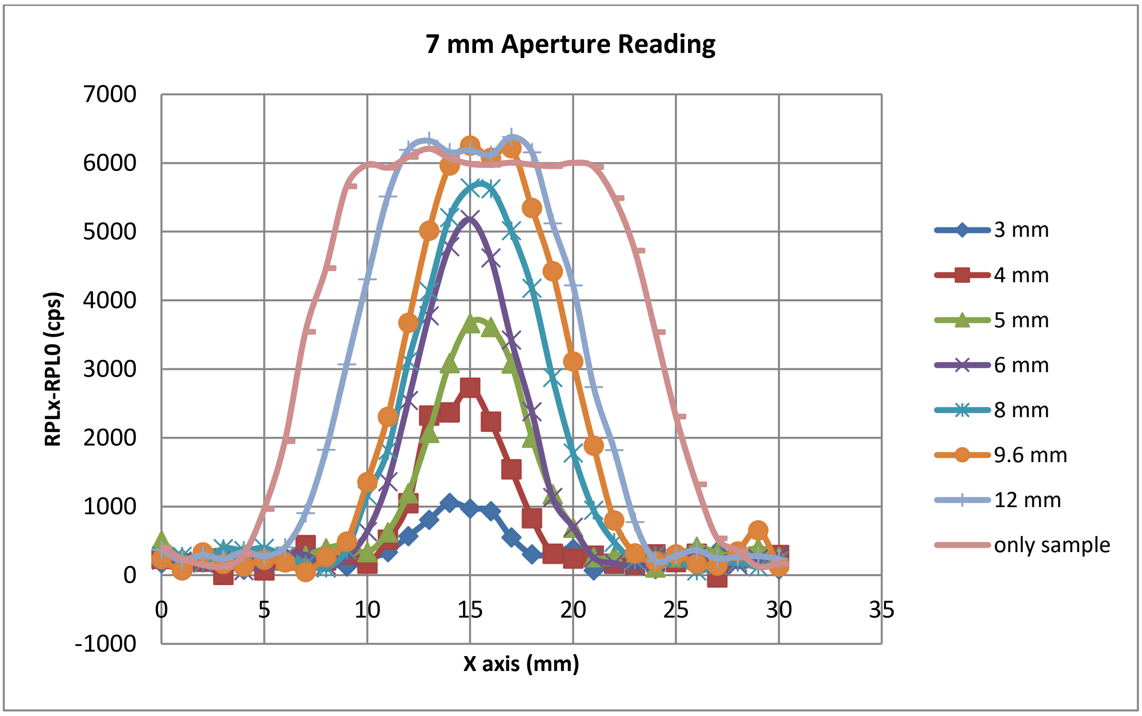



**Figure 21 - Absolute RPL signal of the sample with different hole sized black paper. Only sample represents the sample reading without any black paper on it.**

Results of the 7 mm aperture (Figure 21) show that when the reading area (area not covered by black paper) is increased the peak count rate increases also. Higher peak count rates were obtained for reading areas bigger than the size of aperture. For 7 mm aperture the peak count rates stops increasing for a reading area of 9.6 mm diameter. The maximum peak value might be reached even before 9.6 mm, however data for a diameter between 8 mm and 9.6 mm is not available. If the 9.6 mm case is assumed to be the size at which the maximum count rate is reached, it can be said that a 7 mm aperture RPL signal is actually collected on the surface of 9.6 mm diameter (effective measured surface). The reading aperture area is 38.5 $mm^2$ and the sample surface for 9.6 mm diameter is 72.4 $mm^2$, so the effective measured surface is actually 88% higher than the area of the aperture.

For readings performed with a 5 mm aperture the maximum peak RPL was also observed for sample area of 9.6 mm diameter (same as for a 7mm aperture). In the 3 mm case there was no peak pattern which could be identified. It may be because that thickness of the aperture plastic could be too thick for 3 mm aperture. Results obtained with However 5 mm and 7 mm apertures showed that the surroundings of the sample affect the RPL count rate significantly. In order to prevent the effect of surroundings, sample should be kept as close as possible to the aperture.

### *4.4.6 Spatial Resolution*

After the results of the dose maps in order to understand to spatial resolution of the system new sample set up was prepared. Different thickness of stripes was prepared from RPL paper sheet. Stripe widths were 7 mm, 5 mm, 4 mm, 3 mm and 2 mm respectively. For each group of different sizes irradiated and non-irradiated stripes were prepared and these irradiated and non-irradiated stripes were put in a row to create a dose pattern (Figure 22).

Before irradiation of the stripes, background levels of the each stripe group were read. After the irradiation of the marked stripes (see Figure 22) with 10 Gy, dose responses was subtracted from the background and absolute RPLs were obtained.

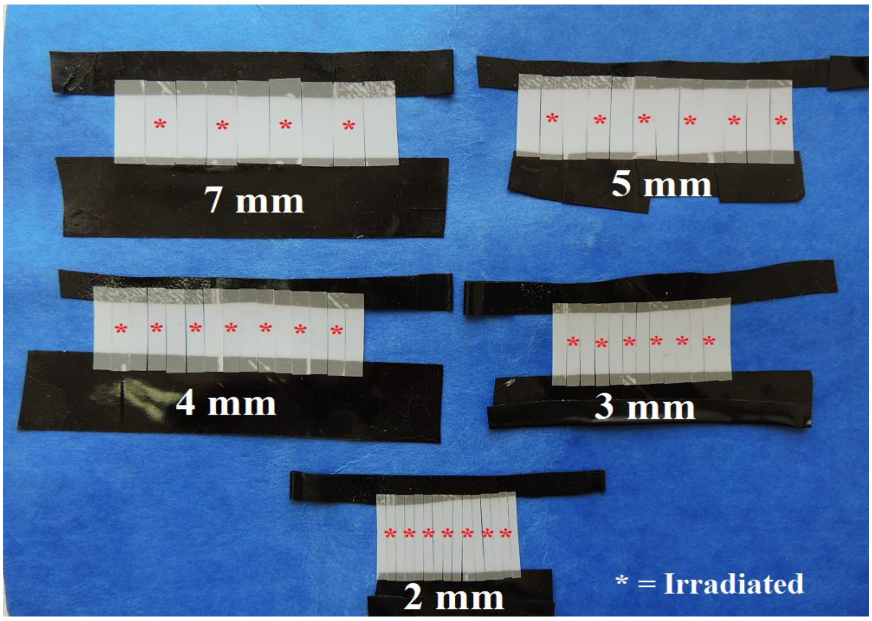



**Figure 22 – Different size of stripe group samples prepared for spatial resolution test.**

| Real Widths (mm) | FWHM of 3 different peaks in each stripe group (mm) | | |
|---|---|---|---|
| 7 | 7.43 | 6.27 | 6.43 |
| 5 | 4.96 | 4.45 | 4.70 |
| 4 | 4.88 | 4.13 | 3.59 |
| 3 | 2.66 | 5.08 | 3.23 |
| 2 | Not possible | Not possible | Not possible |

The patterns of 7 mm stripes which are irradiated and non-irradiated ones have RPL signal difference was around 1900 cps (2500 cps versus 4400 cps). In the other stripe groups the differences were 1500 cps (2500 versus to 4000 cps) for 5 mm stripes, 1400 cps (2400 cps versus 3800 cps) for 4 mm stripes, 800 cps (2800 cps versus 3600 cps) for 3 mm stripe. Peaks of the irradiated stripes could not be seen for 2 mm wide stripe group. The base counts for 3 mm width stripe group higher than the other groups. Since the width of the stripes gets smaller the aperture opening can see other irradiated stripes and receive more counts. Because of that base of the 3 mm group is little bit higher than others.

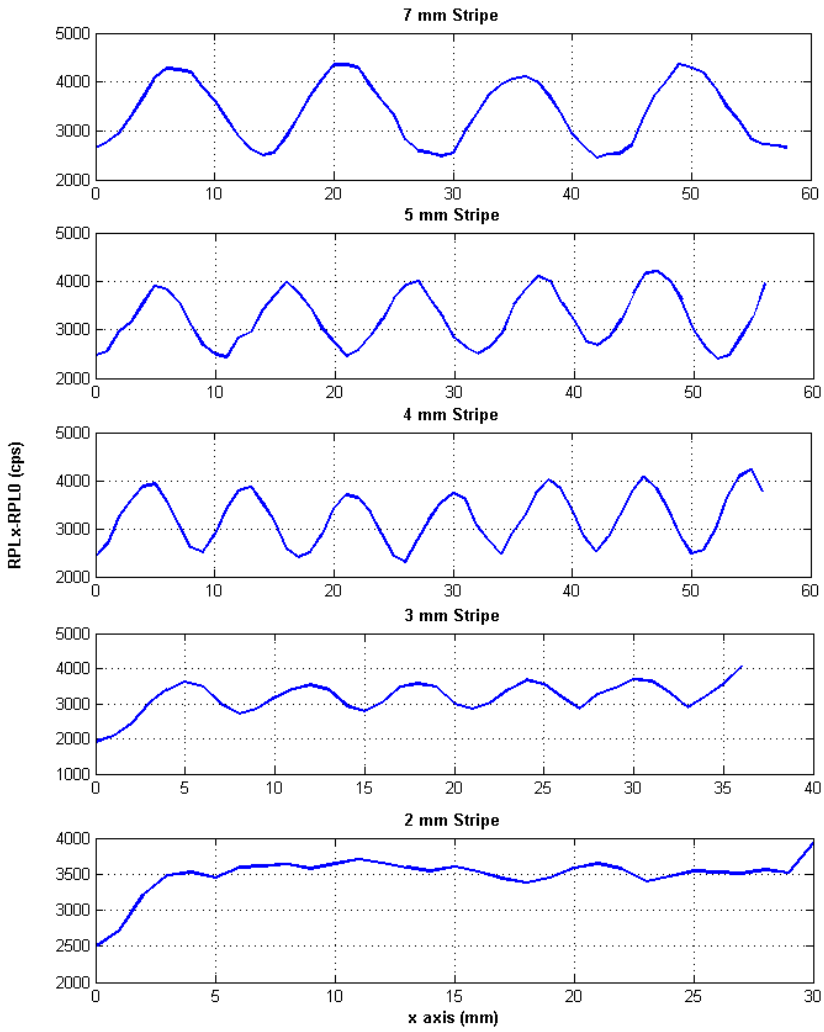



Figure 23 - Absolute RPL signals of different width size (7mm to 2mm) of stripe groups for spatial resolution test

According to Rayleigh Criterion, resolution based on the separation of the two individuals in the system. In order to distinguish two different source in the system, Rayleigh Criterion says between maximum and minimum intensity the difference between them should be at least 26% lower than the maximum one. In this case, when the peaks of the each size of the stripes were studied. It was seen that all stripe groups except 3 mm are relied on Rayleigh Criterion. For 2 mm case it is even not possible distinguish peaks. The Rayleigh Criterion basically used in optical imaging in this case (RPL signals and dose responses) it could be better creating a new criterion for imaging the dose regions. Still Rayleigh Criterion can be a good example to see the spatial resolution.

| **Widths (mm)** | **Difference between Irradiated Stripe and Non-Irradiated Stripe** | | |
|---|---|---|---|
| 7 | 40% | 38% | 38% |
| 5 | 38% | 37% | 35% |
| 4 | 34% | 34% | 37% |
| 3 | 21% | 20% | 22% |
| 2 | Not possible | Not possible | Not possible |

## 5. Conclusion

Coating of $Al_2O_3$:C,Mg dosimetric powder gives a positive dose response however during 1D measurement the sensitivity of the samples was not as good as for mixed samples. However in order to increase sensitivity the thickness of the coating or the percentage of powder in it could be increased to a certain level.

Also during the heating and molding process of coated sample sensitivity loss was seen. In order to protect sensitivity level a protection layer can used over the coated surface.

The Results of UV is really promising for the future. The sensitivity level is higher than Red excitation. However with UV excitation the background levels were found to be higher than with Red excitation cases and this might increase the minimum dose that can be detected with the system. The set of optical filters could be further optimized for UV both for keeping the high sensitivity feature and lowering background.

Results from 2D readings showed important issues to have in mind for the future of 3D DoseMask. The maximum spatial resolution we can obtain now is 4mm. Further optimization can be performed by exploring the 3mm aperture. In order to read small areas the small sized aperture is needed, however in this also results in a loss of sensitivity. Also during the 2D readings effect of the surroundings of the sample and sample's height are significant. Therefore it is important that during 2D readings the sample is positioned very close to the aperture to avoid increasing the effective measured area (and so decreasing the spatial resolution) and to increase sensitivity.

In future, coating device for homogeneously coated surface and a protection layer to protect dosimetric powder can be used. Further study of UV stimulation would be interesting. Also more sensitive counters such as Multi-Pixel Photon Counter (MPPC) can be used to observe low dose levels.

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