FEASIBILITY OF OPTICAL SENSING FOR ROBOTICS IN HIGHLY RADIOACTIVE ENVIRONMENTS.

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ABSTRACT

The application of robotics for repair, refurbishing or dismantling of nuclear installations implies eventually severe radiation resistance requirements on embarked components and subsystems. This is particularly critical when optical sensing is considered. Optoelectronic components and optical fibres are indeed quite sensitive to radiation, and without special design are rapidly out-of-operation in such an environment. This paper reports the results of a series of g irradiation experiments on such devices, and identify their behaviour under radiation. Test results show that carefully selected optical fibres can keep their radiation induced attenuation lower than 0.3 dB/m even up to a total dose of 10 MGy. Temperature annealing can even lower this attenuation down to 0.1 dB/m. On the other hand, commercially available light emitting diodes and photodiodes present attenuations figures up to 15 dB, even after a gamma irradiation as low as 250 kGy. However, properly chosen bias procedures are shown to greatly enhance this figure. The paper concludes by showing the feasibility of optical sensing for proximity measurement and data transmission for nuclear robots used under severe radiation conditions.

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The application of robotics for repair, refurbishing or dismantling of nuclear installations implies eventually severe radiation resistance requirements on embarked components and subsystems. This is particularly critical when optical sensing is considered. Optoelectronic components and optical fibres are indeed quite sensitive to radiation, and without special design are rapidly out-of-operation in such an environment. This paper reports the results of a series of γ irradiation experiments on such devices, and identify their behaviour under radiation. Test results show that carefully selected optical fibres can keep their radiation induced attenuation lower than 0.3 dB/m even up to a total dose of 10 MGy. Temperature annealing can even lower this attenuation down to 0.1 dB/m. On the other hand, commercially available light emitting diodes and photodiodes present attenuations figures up to 15 dB, even after a gamma irradiation as low as 250 kGy. However, properly chosen bias procedures are shown to greatly enhance this figure. The paper concludes by showing the feasibility of optical sensing for proximity measurement and data transmission for nuclear robots used under severe radiation conditions.

I. INTRODUCTION

The application of robotics for repair, refurbishing or dismantling of nuclear installations implies in some cases strong requirements with respect to the radiation resistance for all embarked components and subsystems. This is particularly critical when optical sensing is considered for position or contact perception. Optical sensing covers here not only vision, but also proximity sensing, special types of tactile sensing and short distance data transmission. Examples are fibrescopy, 3D perception by laser triangularisation, anticollision protection by infrared reflection sensors, as well as high speed optical fibre data link. All those techniques are now common on advanced industrial robots.

On the other hand, nuclear power plants require more and more complex remotely operated intervention in highly radioactive environments. Leaving aside accidental conditions, ageing phenomena and plant life extension objectives lead to more frequent off-operational maintenance and repair procedures, refurbishing campaigns, or even real dismantling in some cases. Work must be planned in areas where the γ dose rate can eventually be as high as several hundreds of Gy/h. The equipment to be used in such conditions must be capable to withstand total doses of more than 1 MGy.

In many instances, purely manual control based on camera viewing for instance is difficult and unreliable, due to high complexity of tasks, constrained space, poor vision conditions or unstructured and disturbed environment. The use of advanced computer aided teleoperation reduces operator stress and human errors, enhances both speed and task efficiency, allows for more complex interventions, but requires reliable embarked sensors and processors and a more complex umbilical management. Optical sensing and communication offers interesting solutions, fully assessed on advanced industrial robots. But their transfer on nuclear manipulators can only be considered if proper tolerance to severe radiation environment is guaranteed. A series of γ irradiation experiments[1] has been launched to assess this tolerance for selected, but commercially available components, and to optimize the operational conditions. Particular results for optical fibres and optoelectronic components are shown below. Optoelectronic components and optical fibres indeed show to be quite sensitive to radiation [1],[2],[3]. Several studies have been carried out on damage caused by γ irradiation in optical fibres [4],[5], on photodiodes [6] or light emitting diodes [6] for instance. These studies show that performance degradation (e.g. radiation induced attenuation in optical fibres, decrease of optical output power in light emitting diodes, etc) can be severe in some cases even at low doses.

II. EXPERIMENTAL SET-UP

A. Optical Fibres

Six commercially available pure silica core optical fibres were selected, based on their reported radiation tolerance, their chemical composition and their manufacturing conditions. They are listed in table 1.

They were irradiated in the so-called CMF gamma irradiation facility [7] of the BR2 reactor, Mol, Belgium, which uses spent fuel elements as radiation source. A schematic view of the experimental set-up is shown in Fig. 1. The fibres under irradiation were monitored on line with a computer based data acquisition system at a dose rate of 30 kGy(Si)/h up to a total dose of 10 MGy.

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[1] The above work has been performed under partial support of the commission of the European Community, particularly in the frame of the TELEMAN ENTOREL Project (Contract F12T-CT-0011)

Table 1 : List of Optical Fibres

Ref. Label	Manufacturer	Type	ϕ Core (µm)	Numerical aperture	OH Content
M1	Mitsubishi	ST-R100C(FV)V 100	100	0.20	low
Q1	Quartz & Silice	AS 200/280	200	0.21	high
Q2	Quartz & Silice	AS 100/140	100	0.21	high
P1	Polymicro Technologies	FBP 200220240	200	0.22	low
P2	Polymicro Technologies	FHP 200220240	200	0.22	high
R1	Raychem	VSC 200/280	200	0.22	high

The fibres were wound on a metallic cylinder with a diameter of 70 mm and measured using two types of light sources : a LED source at 850 nm and a white light source with three bandpass filters (400 nm to 700 nm, 700 nm to 1000 nm, 1000 to 1800 nm). The light sources were used in chopped mode, with a chopper frequency of 270 Hz to limit parasitic light effects. Experimental temperature was about 60 °C.

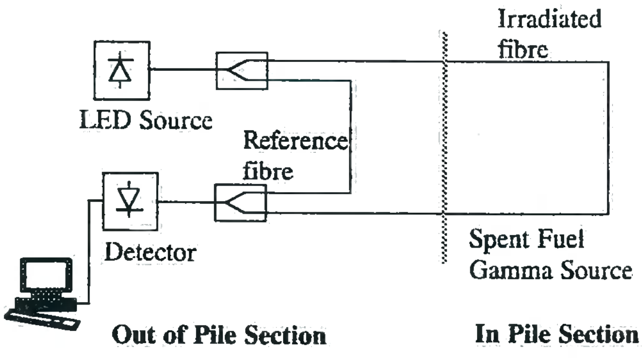

Figure 1 : Schematic view of the experimental set-up for irradiation of optical fibres

A fibre length of 30 m was subjected to radiation. For each of them, an identical unirradiated counterpart served as a reference to measure only with high accuracy the radiation induced optical attenuation.

B. Optoelectronic Components

The test covered three types of commercially available light emitting diodes (LED), one type of phototransistors (PT), one type of PIN photodiodes (PPD) and one of avalanche photodiodes (APD) (Table 2). Three samples were irradiated for each selected component.

The irradiation was performed with a ^{60}Co gamma source [7] at a dose rate of 350 Gy(Si)/h. Two irradiation campaigns lead to total integrated doses of respectively 70 kGy and 260 kGy. Experimental temperature was about 28 °C.

The components were mounted on a polyimide resin based printed circuit board. Some of the components where mounted in pair (LED's connected to phototransistors or photodiodes) , forming a set of simple optocouplers. The following pairs were thus made : LED1/PT1, LED2/APD1, LED5/PT2, LED6/APD2, LED9/PPD1 and LED10/PPD2. The remaining components were mounted as stand alone and provided post irradiation data.

Table 2 : List of optoelectronic components

Ref. Label	Component	Manufacturer	Type
LED 1,2,3	GaAs LED	Honeywell	SE 5455-3
LED 4,5,6	GaAs LED	Honeywell	SE 3455-3
LED 7,8,9	AlGaAs LED	NEC	NDL 4103 A
PT 1,2,3	Si Phototransistor	Honeywell	SD 5433-3
PPD 1,2,3	Si PIN Photodiode	NEC	NDL 1102
APD 1,2,3	Si Avalanche Photodiode	NEC	NDL 2102

Fig. 2 gives a view of the experimental set-up.

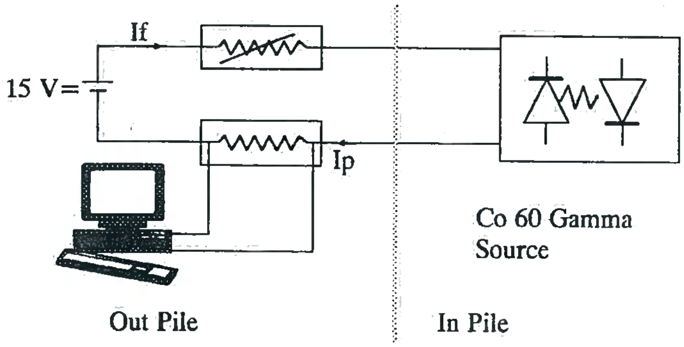

Figure 2 : Schematic view of the experimental set-up for irradiation of optoelectronic components.

A constant forward current (I_f) of 30 mA DC was applied to all LED's. The resulting photocurrent (I_p) on the phototransistor or photodiode was measured with a PC based data acquisition system. At specific intervals, the forward current (I_f) was swept from 10 mA DC to 60 mA DC in steps of 5 mA. The resulting changes on the photocurrent (I_p) were measured to investigate the sensitivity of LED-photodiode/ phototransistor pair.

III. EXPERIMENTAL RESULTS AND DISCUSSION.

This section presents specific irradiation results obtained both for fibres and for optoelectronic components. Resulting measurements are presented in the following figures as a function of the accumulated dose and the observed behaviour is discussed.

A. Optical fibres

Fig. 3 shows the radiation induced attenuation of the M1 optical fibre. The light source used is the LED at 850 nm. At the start of the irradiation the radiation induced attenuation increases very rapidly up to 0.25 dB/m. However, further increase is small and a fairly stable value around 0.37 dB/m is obtained at an accumulated dose of 4 MGy.

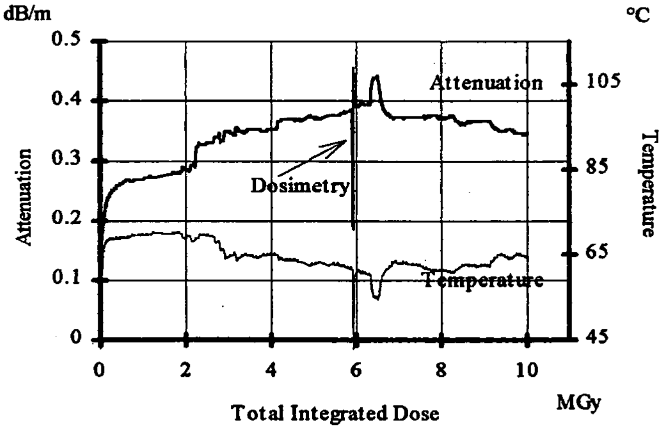

Figure 3: Radiation induced attenuation on M1 optical fibre at 850 nm

Some interesting transient phenomena were observed. At a total dose of about 6 MGy, a dosimetry was performed. At that time the fibres were removed from the gamma source for one hour , but were kept monitored on-line at room temperature. The induced attenuation decreased very fast in the absence of radiation. When the irradiation resumed, a transient increase is noticed, as was seen at irradiation start. Directly after this rise in attenuation, the increase in temperature (from room temperature to 60° C) results in a temperature annealing, lowering the radiation induced attenuation by 0.05 dB/m. This influence can in fact be observed during the whole experiment : at 6.3 MGy, a temperature drop as small as 8 °C caused an increase of 0.05 dB/m for the induced attenuation, towards the end of the irradiation, were the temperature was slightly higher, the induced attenuation lowers.

Fig. 4 presents the radiation induced attenuation for the same fibre at different wavelengths. The figure shows clearly that the induced attenuation is higher for lower wavelengths, but that the evolution of the induced attenuation as a function of accumulated dose is the same over the whole measured wavelength range.

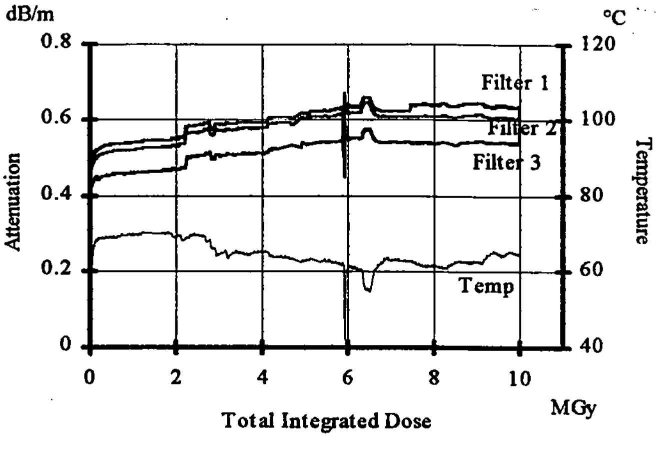

Figure 4: Radiation induced attenuation of Mitsubishi optical fibre for different wavelengths.

The radiation induced attenuation for the two Q1 and Q2 optical fibres is shown in fig. 5.

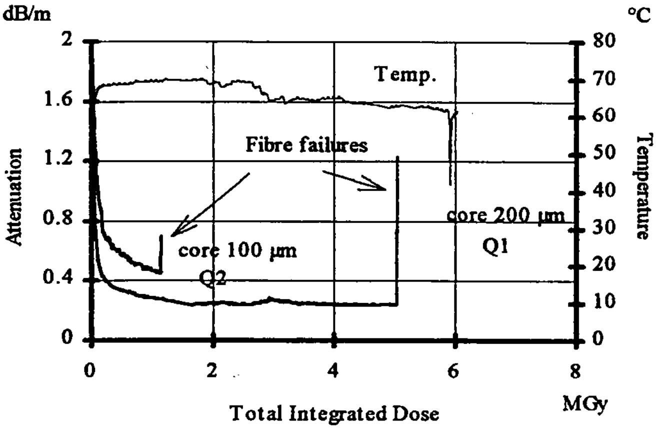

Figure 5 : Radiation induced attenuation for Q1 and Q2 optical fibres (core diameter : 100 µm and 200 µm)

For both fibres, a transitory increase at irradiation start is observed: the induced attenuation reaches a value of almost 2 dB/m. Afterwards, a fast recovery lead to an induced attenuation of about 0.25 dB/m for Q1 and 0.5 dB/m for Q2. This transient phenomena on these two high OH content fibres is different from the transient phenomena of the M1 fibre. The difference in induced attenuation is quite consistent with the core diameter difference between both fibres. At a total dose of respectively 1.8 MGy and 5 MGy, mechanical fracture occurred. Post irradiation examination showed that the polymer cladding had become brittle. However, thermal stresses combined with the mechanical forces due to fibre winding are probably the main causes for the observed fractures.

The results for the P1 and P2 optical fibres are presented on Fig. 6. OH content is low for P1, high for P2.

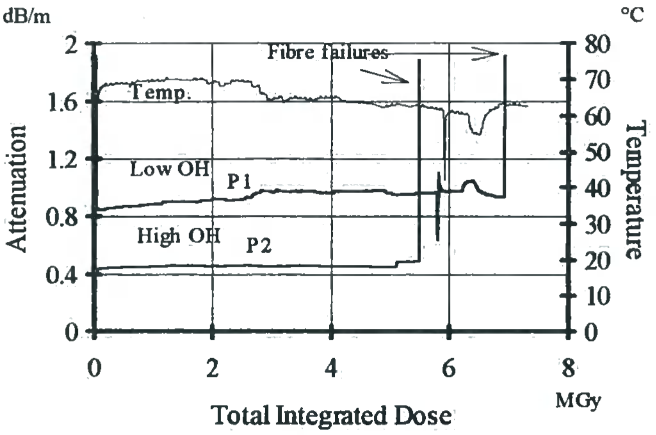

Figure 6: Radiation induced attenuation for P1 and P2 optical fibres

P2 presents a similar behaviour to the one presented on Fig. 3 with a sharp increase of the induced attenuation at the start of the irradiation, and a stabilisation afterwards at approximately 0.5 dB/m. The P1 fibre on the contrary shows in a similar way as the Q1 and Q2 fibres, a transitory phenomena at irradiation start with a peak value up to 2 dB/m and a rapid stabilisation at half this value. A slight increase can be observed afterwards up to 0.9 dB/m. This is particular for low OH content fibres where clearly the radiation and heat induced phenomena have a different relative time ratio. The temperature dependency however is very similar to the one observed for the M1 fibre. At total dose of respectively 7 MGy and 5.5 MGy, fibre fractures occurred. Post irradiation measurements showed that the fractures occurred for the same reasons as the fibres P1 and P2.

The R1 fibre (also with low OH content) showed at the start of the irradiation a similar behaviour, i.e. a fast increase of induced attenuation, but a mechanical fracture occurred very early at a total dose of only 20 kGy.

The results obtained show that radiation induced attenuation can be kept to acceptable figures with properly selected fibres. An attenuation of 0.3 to 1 dB/m allows easily short distance data communication and light transport for optical sensing. Temperature annealing can even lower this attenuation to less than 0.2 dB/m. Such an annealing can be obtained not only by a heat treatment, but also by photobleaching, i.e. transmission of high power light beams. Larger core diameter enhance clearly the transmission performance, as does a high OH content in the silica core [2]. High OH contents are also responsible for sharper transient phenomena.The results present also remarkably stable values after a transient increase at irradiation start, stressing the need for pre-irradiation on all fibre components to be used in nuclear environment. The strong non-linear character of the radiation induced attenuation curves emphasises the validity of high total dose tests requirements, as mere extrapolation from low dose data cannot predict further behaviour. Mechanical fractures occurred on uncoated fibres due mainly to thermal and mechanical stresses, and partly to the embrittlement of the polymer cladding. The only coated fibre, M1, was kept undamaged, although it was wounded the same way as the other samples. The extra coating, which was Kevlar-based, actually provides mechanical relief capabilities.

B. Optoelectronic components

Fig. 7 shows the measured photocurrent I_p of a Honeywell Si phototransistors PT1 as a function of the accumulated dose. The lightsource was a Honeywell GaAs LED1. The test campaign occurred in two steps, one up to a total dose of 70 kGy, a second one up to 260 kGy.

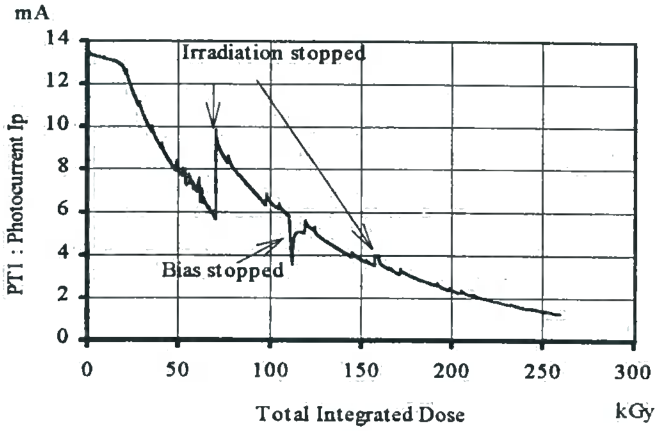

Figure 7: Photocurrent of phototransistors PT1 vs Dose

The photocurrent remains almost constant up to a dose of 20 kGy, and then decreases steadily from 13 mA down to 6 mA (at 70 kGy). The small spikes on the curve are caused by the second measurement procedure performed on the components. The resulting short increase of optical output power in the LED-phototransistor pair clearly induces a small annealing process. When the irradiation stops (at 70 kGy) a very fast recovery in photocurrent occurs, indicating that keeping the phototransistor under constant bias when not irradiated is advantageous.

During the second part of the test, the photocurrent degrades further along the same trend and the observed phenomena confirm the influence proper bias. At approximately 110 kGy for instance, the bias was interrupted and a loss of performance was clearly measured. Annealing by temporarily increasing the optical power could then restore the current to its former level. On the other hand, interrupting the irradiation (at 160 kGy) but keeping the bias shows again an increase of the photocurrent.

The sensitivity measurements performed on the same phototransistor are presented on Fig. 8. The resulting photocurrent Ip on the phototransistor PT1 is traced as a function of the If current on the LED source.

Sensitivity for low values of forward current applied to the LED, i.e. low values of optical power, decreases very fast with increasing total doses. For a total dose of more than

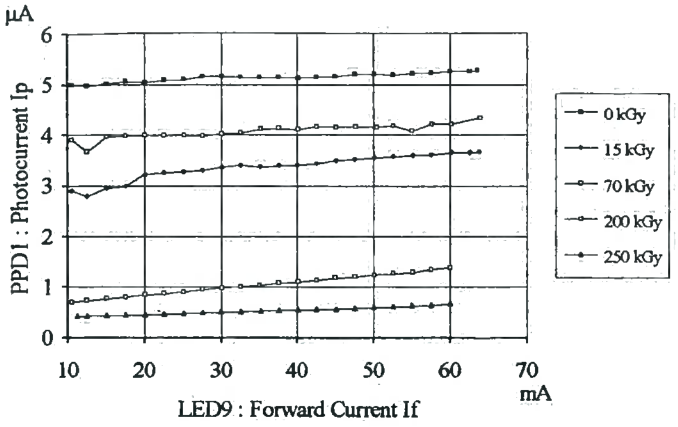

Figure 12: Sensitivity of Si PIN photodiode PPD1

The above figures clearly show that optoelectronic components are indeed very sensitive to gamma radiation. A general loss of performance for a pair LED-phototransistor/photodiode is typically of the order of 10 to 15 dB. Specific operating conditions can however significantly enhance these figures. Phototransistors show for instance less degradation when used at high levels of optical output power and tend to degrade more rapidly when not kept constantly under bias. Photodiodes on the other hand show less degradation when not kept under constant bias. Presence or absence of radiation also shows different results for phototransistors or photodiodes.

IV. CONCLUSION

Optoelectronic components and optical fibres have been subjected to a series of severe gamma radiation tests. Degradation phenomena have been observed leading to induced attenuation, reduction of sensitivity and increased dark current. However, the reported results show that

- carefully chosen fibres present stable induced attenuation curves at levels compatible with short distance light transport and datacommunication,
- particular attention must be put on optical fibre cable cladding, and the way mechanical stresses are absorbed, as slight radiation induced embrittlement renders this issue more critical,
- optoelectronic components did not experience any failure. Dark current increase and lack of sensitivity are kept into tolerable bounds even after significant doses, at least if properly designed circuits are used. Attenuation of 20 to 30 dB are commonly seen as acceptable in communication links.
- specific bias procedures can however significantly enhance optoelectronic components performance, but the procedures depend on the type of semiconductor used.

The reported results show that many optical applications can be considered feasible on robotic devices, even in highly radioactive environment. Taking into account the reported radiation induced changes, the following examples are easily hardened by choosing proper components or operational procedures : laser triangulation for 3D proximity perception, remote vision using fibrescopy, infrared sensing for proximetry or collision avoidance, pressure or temperature measurement using fibre sensing including distributed sensors, optical data communication for video and sensor signals, etc . Using the reported results, an optical fibre bundle has been for instance manufactured, capable to perform remote infrared proximity sensing in severe gamma radiation fields. Tests up to 300 kGy showed practically no degradation of significance for the device. Further work is planned on fibre sensors, laser triangulation and optical communication.

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70 kGy the saturation region of the phototransistor can not be reached any more.

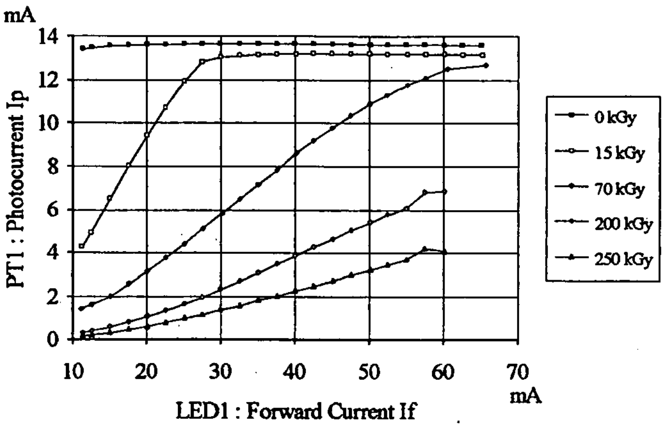

Figure 8: Sensitivity of Honeywell phototransistor PT1

These types of measurements however do not indicate whether or not the degradation of the pair LED/Phototransistor is due to the degradation of LED phototransistor or both. Post irradiation measurements showed that radiation damage to the LED's is present, but at much lower levels than for the phototransistor: degradation of the pair is for 90% or more due to the degradation of the phototransistor.

Fig. 9 shows the photocurrent Ip of the NEC avalanche photodiode APD1 used with a Honeywell GaAs LED2 as light source.

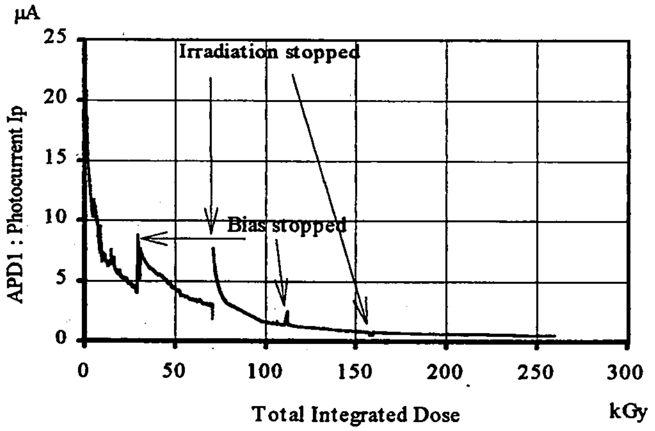

Figure 9: Photocurrent of Si avalanche photodiode APD1

A fast decrease of photocurrent at the beginning of the irradiation is noticed. The sudden increase at a dose of 29 kGy is due to a short interruption of the bias and indicates that here, contrary to phototransistors, keeping the component constantly under bias is disadvantageous. A similar difference can be seen when irradiation is stopped for a short time. At 160 kGy, the irradiation was deliberately interrupted for five hours. The components were kept under constant bias and were kept monitored on-line all the time. Directly after resuming the irradiation the photocurrent decreases again to the same level prior to irradiation stop.

Sensitivity measurements, as shown on Fig. 10, show the decrease in performance with accumulated dose. As the dose increase, the photocurrent decreases and this happens with the same relative amount for low values of forward current I_f as for higher values. For total doses of more than 200 kGy, the sensitivity is very low, and only a small variation of photocurrent I_p can be observed

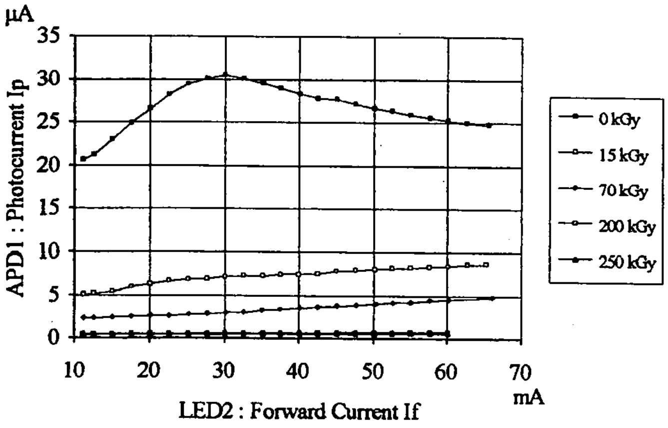

Figure 10: Sensitivity of NEC Si Avalanche photodiode APD1

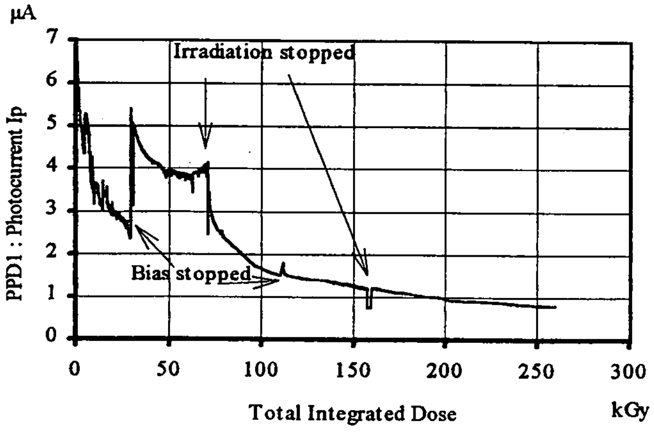

Figure 11: Photocurrent of Si PIN photodiode PPD1

Figs. 11 and 12 show respectively the photocurrent of the NEC Si PIN photodiode PPD1 used with a NEC AlGaAs LED7 and the corresponding sensitivity. The results are quite similar to those of the avalanche photodiode.