Radiation Characterization and Test Methodology Study of Optocouplers Devices for Space Applications

R. Mangeret*, L. Bonora**, T. Bouchet**, D. Peyre**
R. Harboe-Sorensen °

* Astrium, 31 rue des cosmonautes, 31077 Toulouse cedex, France.
** Astrium, 37 av. L. Breguet, BP1, 78146 Vélizy-Villacoublay, France.
° ESA/ESTEC, Noordwijk, The Netherlands.

Abstract

This work investigates the degradation of several different optocouplers for space applications. Hardened and standard (unhardened) types are tested under proton, neutron and Co^{60} irradiations under various bias, fluence and dose rate conditions. An attempt to define an industrial cost-effective test procedure is proposed.

I. INTRODUCTION

Optocouplers, or optoisolators, are widely used in space applications where particles such as protons are of primary concern. But these devices are known to be strongly degraded under proton irradiations which generate both displacement damage and total ionizing dose (TID) [1,2,3,5,6]. Indeed, optocouplers consist of a LED (AlGaAs or GaAs), often highly susceptible to displacement damage, and of a silicon phototransistor (or a couple silicon photodiode and transistor) affected by both effects.

In order to evaluate this sensitivity, and which parameters influence it, experiments were conducted with protons (three energies), Co^{60} (two dose rates) and neutrons (a potential alternative for protons). Seven optocouplers types, three hardened and two unhardened or standard (from three manufacturers), were tested using three bias conditions during irradiations.

Proton results are presented for the real particle fluences and for equivalent fluences, calculated with NIEL values extracted from Barry's work [4]. Comparisons are made between protons and Co^{60} effects. But, as proton beams renting is very expensive, some comparisons are also made between protons and the coupled neutrons+dose as an attempt to define an industrial cost-effective method for optocouplers testing. A TID correction is applied in that case as neutrons only induce displacements whereas protons also deposit an amount of dose depending on their energy.

II. EXPERIMENTAL CONDITIONS

Optocouplers tested are:

- for the hardened ones, the 66099 from Micropac (Mii), 66168 (Mii) and 249OLH (Isolink).
- for the unhardened, the 4N49 (Mii, Optek and Isolink) and the 66163 (Mii).

The following table gives available information about the technology used:

Type	LED	Output
66099 Mii	660 nm (AlGaAs)	Photodiode + 2N2222 transistor
66168 Mii	660 nm	NPN Phototransistor
249OLH Isolink	No information	NPN Phototransistor
4N49 (all)	880 nm (AlGaAs for Mii)	NPN Phototransistor
66163	880 nm (GaAs)	NPN Phototransistor

Measured parameters are:

- 7 CTR (Current Transfer Ratio with increasing input currents I_F and two V_{CE})
- 2 V_{CEsat}
- V_{fwd} and I_R

Degradations were noticed on the two V_{Cesat} measurements whereas no changes were found for V_{fwd} and I_R. The main degradation affects the Current Transfer Ratio, or CTR, which is defined as the ratio of collector current (Ic) to the LED forward current (I_F).

$$CTR = I_C / I_F$$

Data presented primarily focus on CTR1 measurements, the most affected electrical parameter measured at a low input current (I_F = 1mA) and a low V_{CE} (5V) for the output transistor.

For each irradiation exposure, 5 or 6 parts of each type, were used.

All these optocouplers, under the various bias conditions, have been exposed to three irradiation types:

- protons: the proton energies are 15, 60 and 200 MeV
- neutrons: the neutron energy is 1 MeV
- Co^{60}: two dose rates of 0,13 and 50 krad(Si)/h.

III. RESULTS OVERVIEW

III.A. CTR degradation with cumulated dose (Co^{60})

Figure 1 presents a comparison between Low Dose Rate (LDR) and High Dose Rate (HDR) exposures for several different parts.

For both hardened and unhardened parts, damage is more important at low dose rate. This can be linked to enhanced surface recombinations that degrade more significantly the photoresponse (1st order) and the current gain (2nd order) of the output silicon phototransistor in the low dose rate case.

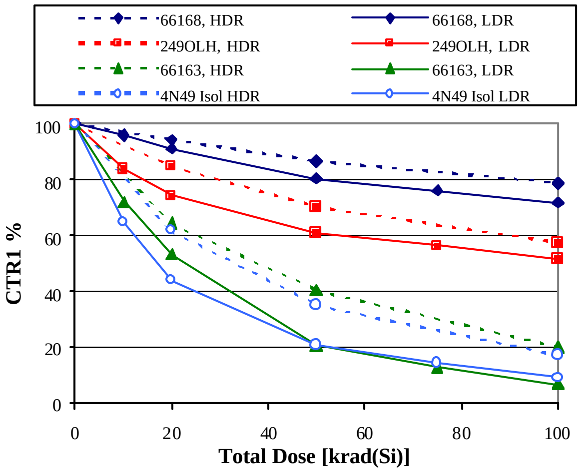

Figure 1: Comparison between parts under Co ^{60} exposures

The influence of bias conditions during irradiation (I_F = 0, 1 or 10 mA) is also examined.

Most of the studied parts (hardened or standard) present a clear irradiation biasing dependence at low and high dose rates, the higher the forward current (I_F) the lower the degradation. The 249OLH is an exception, no irradiation biasing influence appearing under fixed dose rate. A significant device to device degradation variation under identical experimental conditions does not allow a clear conclusion for the 66099.

Figure 2 presents the bias influence during irradiation (LDR and HDR) for 66168.

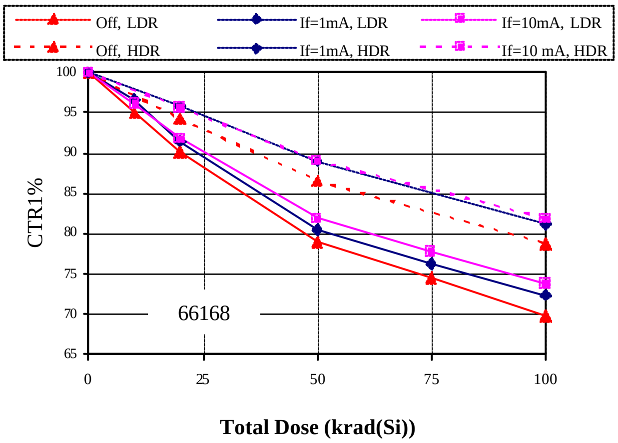

Figure 2: bias conditions influence during irradiation LDR or HDR for 66168.

Finally figure 3 presents, for each type tested, the worst degradation i.e. at low dose rate and without bias during irradiation (or the average value for all bias if no effect is noticed (249OLH) or if wide result variations appear (66099)).

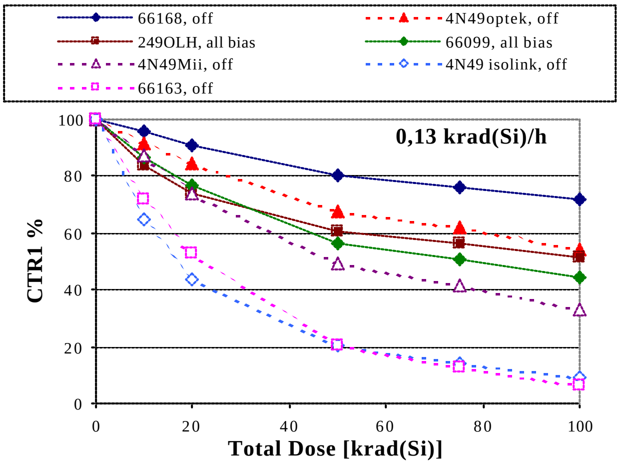

Figure 3: Respective CTR1 degradations at LDR, no bias (or average value for all bias if no effect)

III.B. CTR degradation with protons

Figure 4 presents a comparison between 66168 CTR1 degradations (100 $CTR1/CTR1_0$) under real proton fluences.

An important point to notice on figure 4 is that, for a given real fluence, damage is appreciably more important for the low energy protons. This can be noticed for all the parts studied.

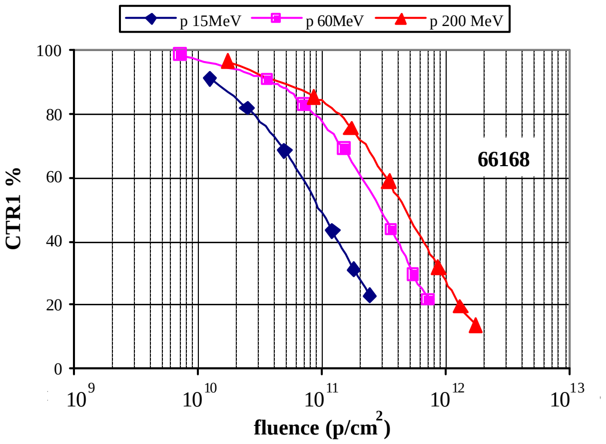

Figure 4: CTR1 degradation under real protons fluences for 66168.

The influence of bias during proton irradiations is also examined.

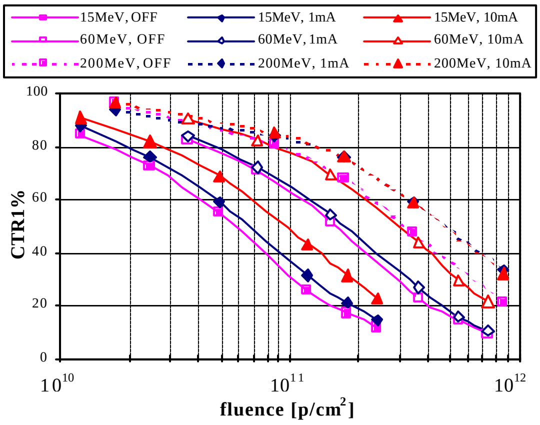

Figure 5: bias influence during proton irradiations for 66168

As for total dose, most of the parts (hardened or standards) present a clear dependence, for all proton energies, to bias conditions during irradiations. Biased parts (I_F = 1 or 10 mA) are less degraded than parts remained off during exposures. The 249OLH remain an exception, no irradiation biasing influence appearing.

All the CTR1 degradations are presented on figure 6, for a given proton energy (60 MeV) and for parts remained off during irradiations. In other proton energy or bias configurations, the different types exhibit the same kind of behaviour.

As expected, the hardened devices (66099, 66168 and 249OLH) are significantly less damaged than unhardened ones.

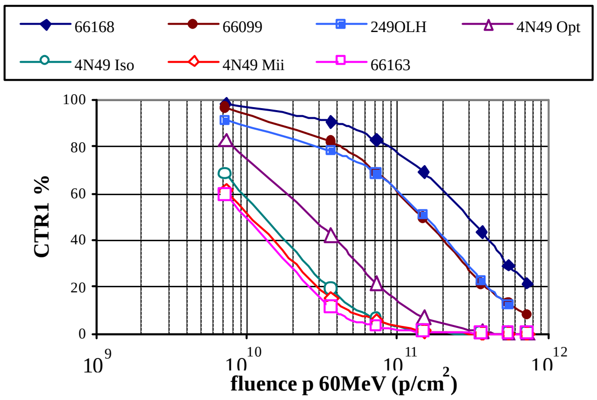

Figure 6: Comparison, for all types, between CTR1 degradations under 60 MeV proton irradiations.

III.C. CTR degradation with neutrons

Figure 7 presents the CTR1 degradation of all studied parts submitted to 1 MeV neutron irradiations. Results presented are for parts that remained off during exposures (maximum degradation). Wide differences appear first between hardened and unhardened devices, as expected, but also between identical types from different manufacturers (4N49). Hardened (to displacement damage) devices are significantly more tolerant than unhardened ones.

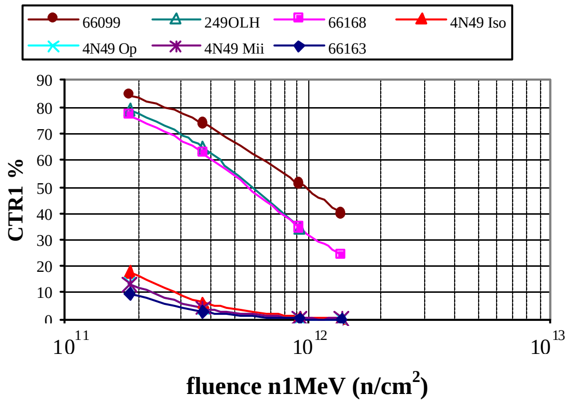

Figure 7: comparison between devices under neutron fluence

Bias effects during irradiations are also investigated. Some slight differences appear between the three bias conditions. For every types and manufacturers, and as for protons and Co^{60}, the worst case is for unbiased parts (off), parts biased under I_F = 10 mA being the less damaged.

Figure 8 presents these results for the 66168 Mii.

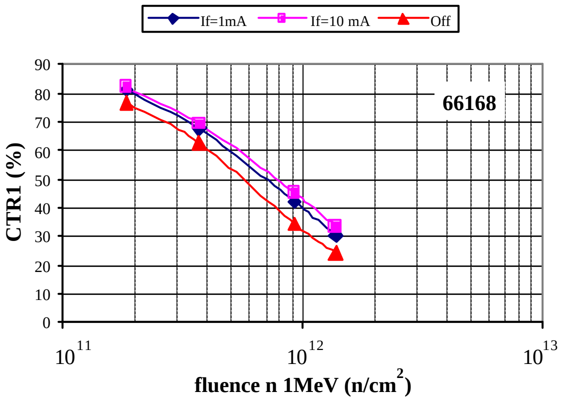

Figure 8: Bias effects during neutron irradiations for 66168

III. D. Degradation of other measured parameters

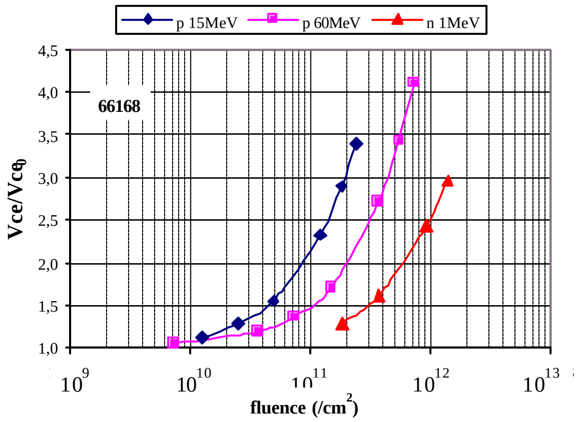

Figure 9: V_{CE} changes under protons/neutron irradiations for 66168

CTR is the more affected parameter, but not the only one. If V_{fwd} and Ir changes are negligible after any type of irradiation, Vcesat presents, on the contrary, significant degradations. No noticeable differences appeared between results for the various biasing conditions during irradiations. Thus, figure 9 presents Vce_{sat1} changes under various particle exposures for 66168. The same kind of behaviour is observed for all other optocoupler types, hardened or not.

IV. DISPLACEMENT DAMAGE AND IONISATION CONTRIBUTIONS TO TOTAL DEGRADATION

The relative effects of displacements and ionizing dose are presented on figure 10 (66168) and figure 11 (66163). The CTR1 degradation is given as a function of the TID deposited by the three proton types and by a Low Dose Rate Co^{60} irradiation for parts irradiated off.

All types, hardened or standard, exhibit far more damage under proton exposures than under Co^{60} γ rays (1.17 and 1.33 MeV).

These results indicate that protons generate both ionizing and displacement damage, the latter being the dominant effect.

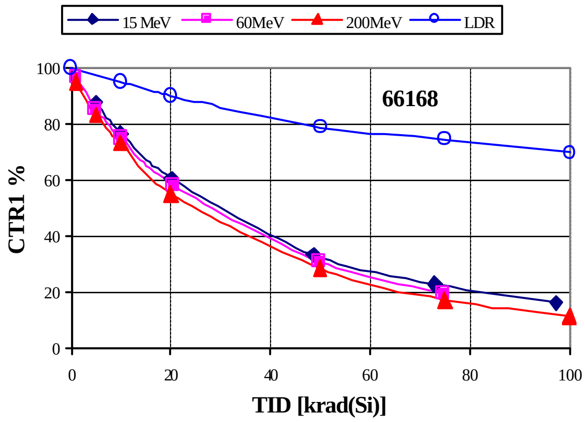

Figure 10: Comparison between proton and γ photon effects for 66168 (hardened type)

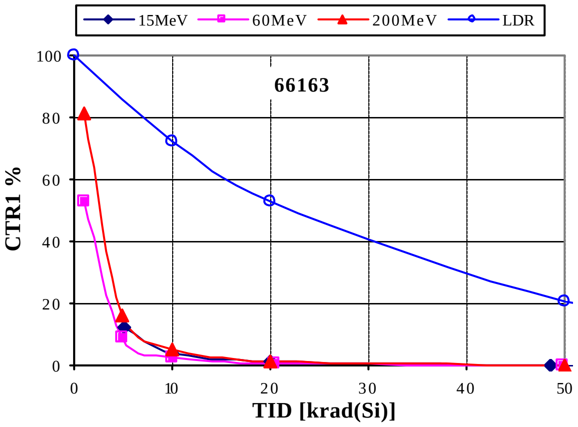

Figure 11: Comparison between proton and γ photon effects for 66163 (standard type).

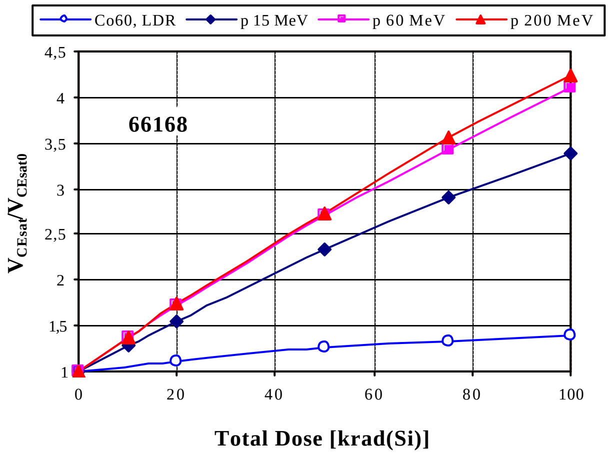

Figure 12: V_{CEsat} degradation under proton and Co^{60} exposures

If V_{CEsat} is considered (figure 12 for 66168), one can notice that degradation is notably more important under proton irradiation.

But V_{CEsat} is a parameter closely linked to the output transistor (or phototransistor) known to be sensitive to γ irradiations as a silicon device. This suggests that displacement damage do not affect only the LED but could not be negligible for the output stage too.

IV) CORRELATION BETWEEN PROTONS AND [NEUTRONS + DOSE] CTR DEGRADATION.

Figures 13 to 16 present the normalized CTR1 degradation as a function of particles equivalent fluences, 15 MeV protons are chosen as a reference.

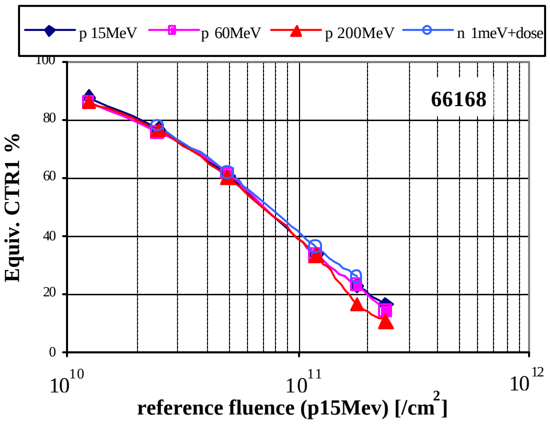

Figure 13: Comparison based on equivalent fluences (real fluence: 15 MeV) for the 66168.

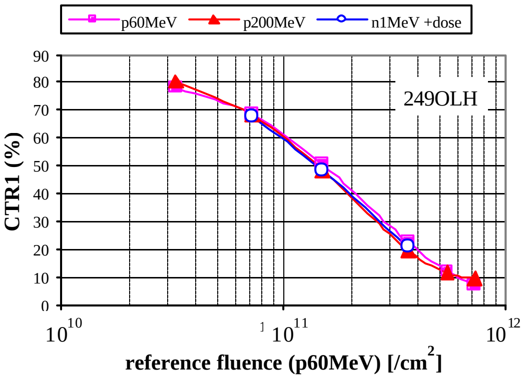

Figure 14: Comparison based on equivalent fluences (real fluence: 60 MeV) for the 249OLH.

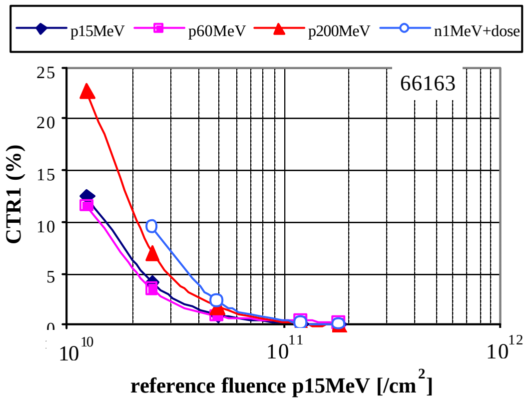

Figure 15: Comparison based on equivalent fluences (real fluence: 15 MeV) for the 66163.

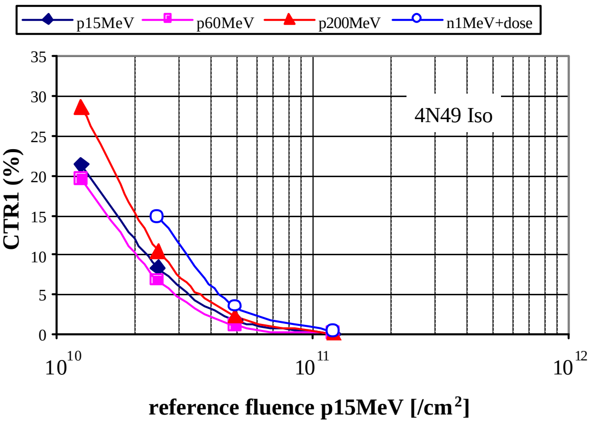

Figure 16: Comparison based on equivalent fluences (real fluence: 15 MeV) for the 4N49 Isolink.

The CTR1 values for 60 and 200 MeV protons, and for the neutrons, are given taking into account the relative effects of displacements for equivalent fluences (NIEL) and the additional TID required (deposited at low dose rate with Co^{60}). This is carried out with a simple calculation based on fitted experimental proton and TID curves. The equivalent monoenergetic particle fluences for different protons or neutrons, are obtained with:

$$\frac{\Phi(p1)}{\Phi(p2)}=\frac{NIEL(p2)}{NIEL(p1)}$$

where $\Phi(pi)$ is the fluence in protons “i”. The neutron to proton equivalent fluence is calculated in the same way.

Results from the different irradiations are in good agreement for hardened devices (66168, 66099 and 249OLH). Degradation caused by protons of a given energy and other protons or neutrons (with equivalent fluence and dose correction) are close together in these cases.

At high fluences, slight differences appear. This may be due to different degradation mechanisms: at low fluence the degradation mainly coming from the LED and, at high fluence, the silicon output (photodiode and transistor or phototransistor) giving some contribution to the reduction of CTR due to no longer negligible displacement damage in these output structures.

More important differences appear between degradation, caused by various energy protons, for unhardened devices, especially at low fluences. The changes in the LED material proportions ($Al_x Ga_{1-x} As$) due to usual higher wavelenght may be an element of explanation for this behaviour. Besides, there are some uncertainties about how to compare damage for different proton energies as the energy dependence of NIEL is different for Si and III-V materials. Some unresolved issues related to NIEL in III-V devices remain.

V. CONCLUSION

Neutron, proton and Co^{60} tests were performed on both hardened and unhardened optocouplers.

Wide differences appear not only between the different types, but also between manufacturers for a given type (4N49). As expected, for all types of irradiations, hardened devices are notably less degraded than standard types.

For each type, the influence of bias during irradiation can be significant for ionising dose and displacement damage. Clear tendencies have been shown whatever testing is performed (protons, neutrons or Co^{60}): OFF during irradiations is a worst case while 10 mA is a best case. This behaviour is probably partly related to the influence of the free carrier density on defect annealing in GaAs.

It was shown, for the devices studied, that displacement damage is the main degradation mechanism (vs total dose). This allows the use of NIEL factor to compare effects of different energies of protons.

The importance of proton energy is examined. Protons of high energy are significantly less damaging, at a given fluence, than low energy ones. These results are similar to those presented in [7].

The main objective of this study was to establish a standard low cost test procedure. This was aimed to be done by correlating the CTR degradation for several proton energies and for the combination [neutron+dose] by the help of the NIEL normalisation. Then, an irradiation at only one energy could be used to establish the degradation expected with a given spectrum.

The NIEL normalisation has been based on Barry et al work [4], with an adapted dose correction if needed.

The good working of the test methodology has been shown for hardened devices. For standard devices, the validity of the applied methodology is not so clear. Further investigations are still necessary but several causes are possible:

- When the NIEL ratio is applied for GaAs, it is considered that the LED is the most sensitive part of the device. However, for high fluences, the degradation contribution of the silicon phototransistor (reduction of the diffusion length in the collector and reduction of the current gain of the phototransistor) may become non negligible.

- Some unresolved issues concerning the NIEL to apply depending on device technology remain [8].

Thus, considering the today knowledge, we recommend to perform proton tests at energy lower than 60 MeV for unhardened devices.

VI) REFERENCES

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