ESA study contract report – Radiation Report
(version for publication, final review)

ESTEC Contract No: 4000102425/10/NL/EM	Subject: ECI2: Development, ESCC Evaluation and Qualification of an European Radiation Tolerant Optocoupler	Contractor: Optoelettronica Italia Srl
ESA CR( ) No:	This is volume No. 23.C (version for publication)	Contractor's reference : A. Maglione

Abstract

This document summarizes the radiation tests and related results, performed by Optoi in the framework of the WP4200, for the abovementioned ESA project.
This document version has been issued after the two subsequent radiation meetings, i.e. pt.1 and pt.2, held with ESA over the phone.

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Contents

List of reference and applicable documents

RD-1: ECSS-E-ST-10-12C *Methods for the calculation of radiation received and its effects, and a policy for design margins*
AD-1: ESCC Basic Specification 22900 *Total dose steady-state irradiation test method*

List of acronyms

DDD : *Displacement Damage Dose*
ECI : *European Component Initiative*
ECSS : *European Coordination for Space Standardization*
ESCC : *European Space Component Coordination*
HDR : *High Dose Rate*
LDR : *Low Dose Rate*
TID : *Total Ionizing Dose*

Introduction

The activities described in the present Radiation Report are related to the Radiation Evaluation, which is the purpose of WP4200. The reported work reviews the experimental activities conducted between March and June 2013.
The contents of this document represent an extract of the more extended report coded P10.004.128.B, which was issued after the *Radiation Review Meeting part 2*, held by teleconference with ESA on 11th July 2013.
The optocouplers under study consist of infrared LEDs and Silicon phototransistors, the latter being manufactured in FBK.
The phototransistors belong to wafers no.6 and 10 of run *ESA121*; they were assembled by Optoi between January and February 2013 (lot codes *AA*-*AB*-*AC*), together with the LEDs, within LCC6 ceramic packages.
The reference code of the resulting component is OIER10.

1. Proton irradiation

1.1. General considerations

Proton irradiations have been conducted in KVI on 10th and 11th April 2013, following the conditions reported in Table 1 as agreed with ESA. The details of this irradiation campaign are reported in **Annex 1**.

Step number	25 MeV (beam 1)	60 MeV(beam 2)	185 MeV(beam 2)
1	4.10^{9}	7.10^{9}	2.10^{10}
2	2.10^{10}	3.10^{10}	7.10^{10}
3	7.10^{10}	8.10^{10}	2.10^{11}
4	2.10^{11}	3.10^{11}	5.10^{11}
5	5.10^{11}	7.10^{11}	1.10^{12}

Table 1: *steps for proton irradiation tests; the reported fluences are measured in p/cm^2*

For each irradiation condition, 3 biased plus 5 unbiased optocouplers were used, all assembled in ceramic LCC6 packages. One MII 4N49 in TO-5 package has been used as reference per each irradiation step; it has been left unbiased and its purpose was to monitor the degradation of characteristics in a well-known commercial product. Non-screened versions of this commercial device have been used for this purpose.
As suggested by ESA, a 1MOhm SMD resistor was connected between the emitter and the base of the phototransistor, in order to make the phototransistor (and consequently the optocoupler) more stable in terms of working point, thus reducing instabilities due for example to the external electromagnetic noise.
Each irradiation step reported in Table 1 has been associated with a different group of devices, leading to an overall number of 120 parts (plus 15 MII references). This was decided because Optoi

preferred to perform in depth measurements on each device before and after each single radiation step, avoiding progressive tests in-situ which were considered too partial and incomplete.
Traceability was possible by means of laser marks on each package lid, using the following serial syntax: *AB01*.
Concerning the biased devices, their biasing conditions were the following: I_f=3mA, V_{ce}=5V.
Specific PCBs were used for this purpose, as shown in Figure 1, hosting specific sockets for the LCC6 type of package and featuring BNC connectors, in compliance with the KVI facility requirements.

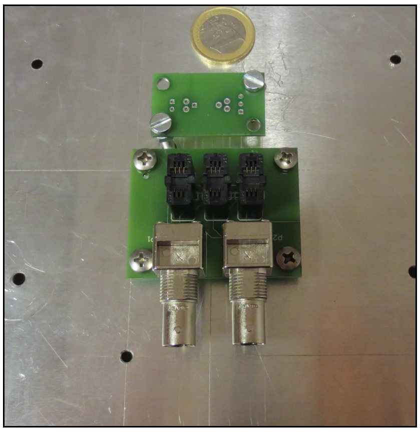

Figure 1: *biasing board mounted on an Aluminium plate, in compliance with KVI's requirements; the upper board is meant to host the unbiased devices, keeping them at the same distance from the beam as the biased ones*

A detailed overview of the tested devices is shown in Table 2; the underlined codes indicate optocouplers with phototransistors belonging to a different wafer, with respect to the majority of the other devices (*ESA121 W6 vs. W10*). The optocouplers with phototransistor belonging to this alternative wafer have been distributed across as many fluences as possible, in order to obtain the best representativeness of such variation within the test plan. Stars indicate unbiased optocouplers exposed to 60MeV (8E10p/cm^2 and 3E11p/cm^2) proton irradiation followed by annealing of several days at room temperature and ageing (168-hour at 100°C).

Fluence	Energy = 25MeV	Fluence	Energy=60MeV	Fluence	Energy=185MeV
4,00E+09	Biased: AA67, AA48, AA53 Unbiased: AA57, AA58, AA54, AA56 MII ref. 18	7,00E+09	Biased: AB00, AB03, AB05 Unbiased: AB09, AB10, AB17, AB14, AC32 MII ref. 9	2,00E+10	Biased: AA18, AA14, AA08 Unbiased: AA00, AA06, AA09, AA19, AC48 MII ref. 1
2,00E+10	Biased: AA55, AA44, AA47 Unbiased: AA43, AA59, AA50, AA51, AA52 MII ref. 17	3,00E+10	Biased: AB06, AB13, AB19 Unbiased: AB20, AB21, AB12, AB22, AC49 MII ref. 7	7,00E+10	Biased: AA17, AA27, AA28 Unbiased: AA20, AA24, AA34, AA35, AC23 MII ref. 2
7,00E+10	Biased: AB77, AB75, AB65 Unbiased: AB90, AC10, AC02, AC05, AA49 MII ref. 10	8,00E+10	Biased: AB24, AB23, AB25 Unbiased: AB26*, AB38*, AB47*, AB27*, AC50* MII ref. 12	2,00E+11	Biased: AA30, AA31, AA33 Unbiased: AA39, AA81, AA82, AA86, AC26 MII ref. 3
2,00E+11	Biased: AB82, AB62, AB63 Unbiased: AB69, AB72, AB79, AB76, AB80 MII ref. 14	3,00E+11	Biased: AB39, AB33, AB29 Unbiased: AB37*, AB42*, AB44*, AB46*, AC52* MII ref. 19	5,00E+11	Biased: AA83, AA85, AA87 Unbiased: AA88, AA90, AA91, AA92, AC28 MII ref. 4
5,00E+11	Biased: AC00, AC03, AC09 Unbiased: AC08, AC01, AC13, AC14, AC15 MII ref. 13	7,00E+11	Biased: AB45, AB59, AB53 Unbiased: AB60, AB49, AB57, AB58, AB56 MII ref. 16	1,00E+12	Biased: AA93, AA94, AA95 Unbiased: AA96, AA97, AA98, AA99, AC29 MII ref. 20

Table 2: *device traceability for proton irradiation tests*

Characterizations before and after irradiation have been conducted in FBK, following a standardized and automated measuring routine as originally described in the *Preliminary Test Plan* (P10.004.31, i.e. Annex no.6 to TN2).

The results are usually summarized in panels as shown in Figure 2; in addition, raw data are generated, allowing detailed extrapolations of trends and drifts, i.e. in the LED direct and reverse biasing conditions, the phototransistor gain and other electrical parameters.

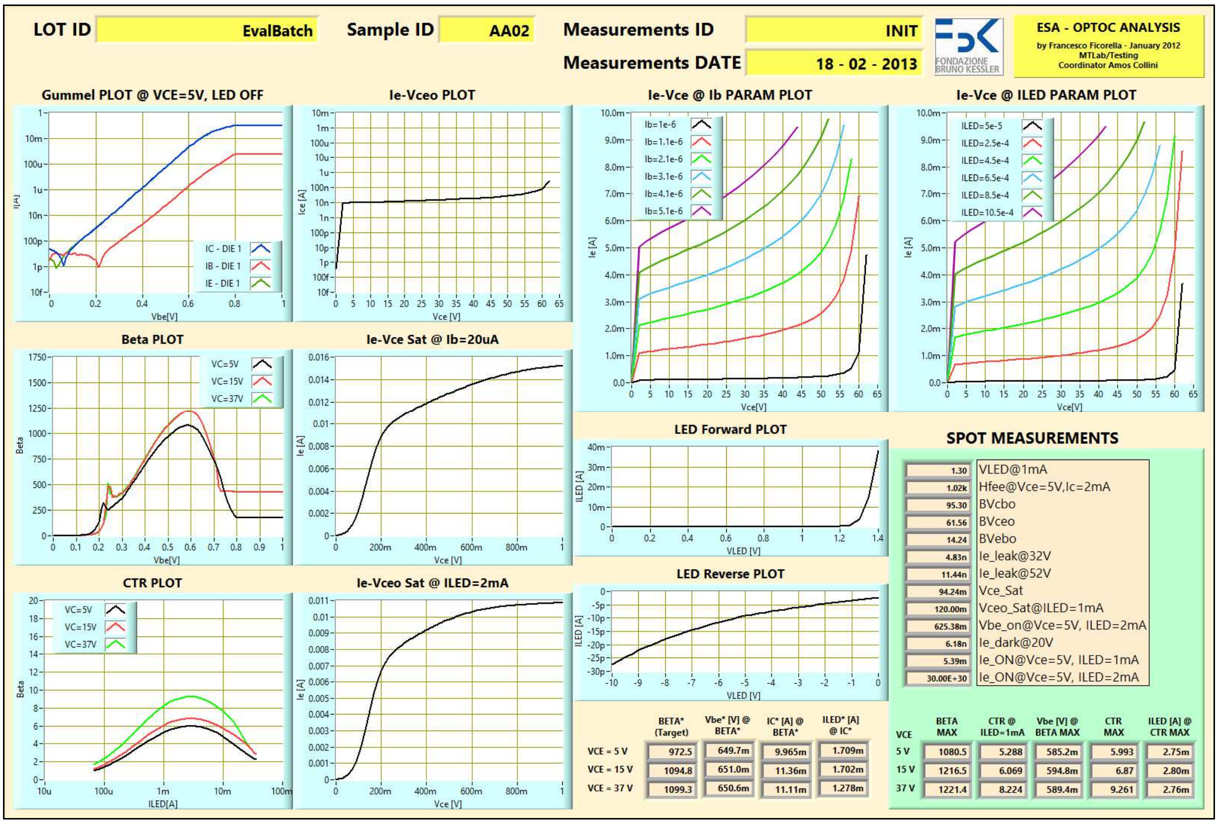

Figure 2: *panel summarizing the main measured parameters*

1.2. Elaborations of the main parameters

The normalized CTR degradation at the three energies of 25, 60 and 185MeV is illustrated from Figure 3 to Figure 5, under nominal test conditions: I_f=1mA, V_{ce}=5V and considering the average of the obtained trends. At that operating condition, the initial absolute value of CTR is around 5 as shown in Figure 2; the absolute value of CTR after proton irradiation are shown from Figure 6 to Figure 8.

The obtained results are considered satisfactory by Optoi, because the normalized CTR decrease is comparable to other optocoupler brands according to Optoi’s knowledge. Although the initial absolute value of CTR might be considered slightly lower than some brands, this limitation might be overcome by Optoi through a more efficient device architecture.

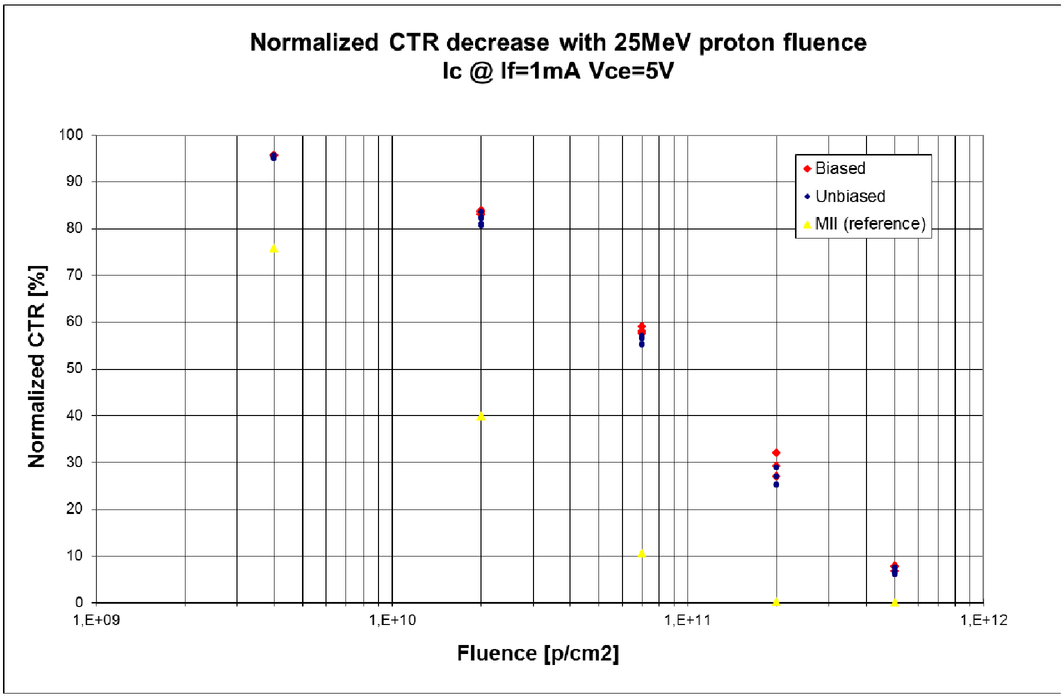

Figure 3: *normalized CTR degradation at 25MeV*

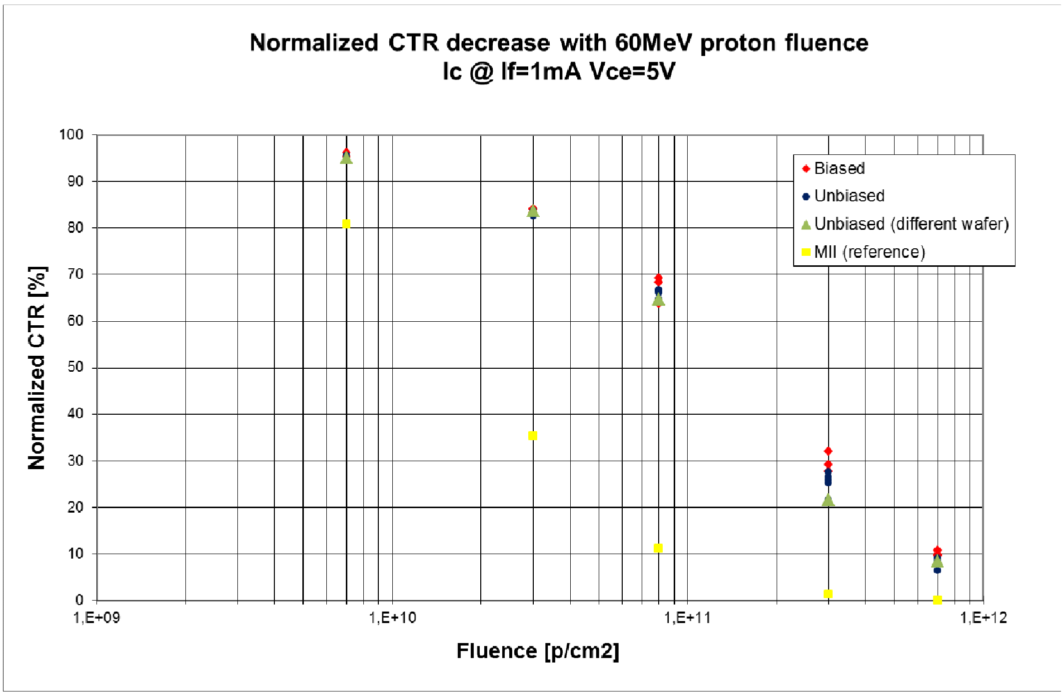

Figure 4: *normalized CTR degradation at 60MeV*

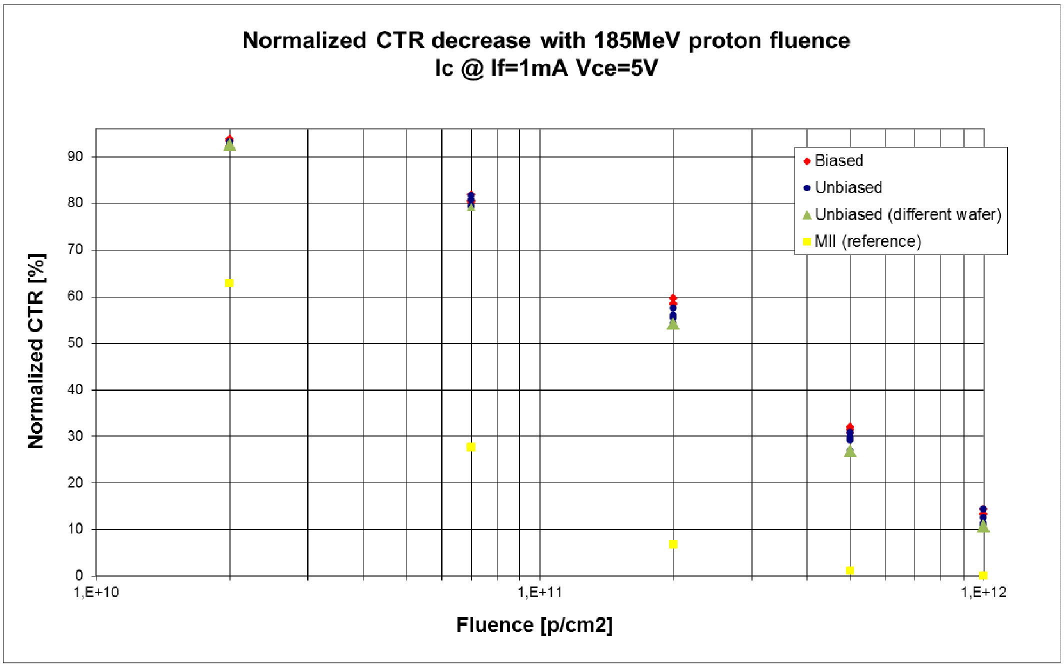

Figure 5: *normalized CTR degradation at 185MeV*

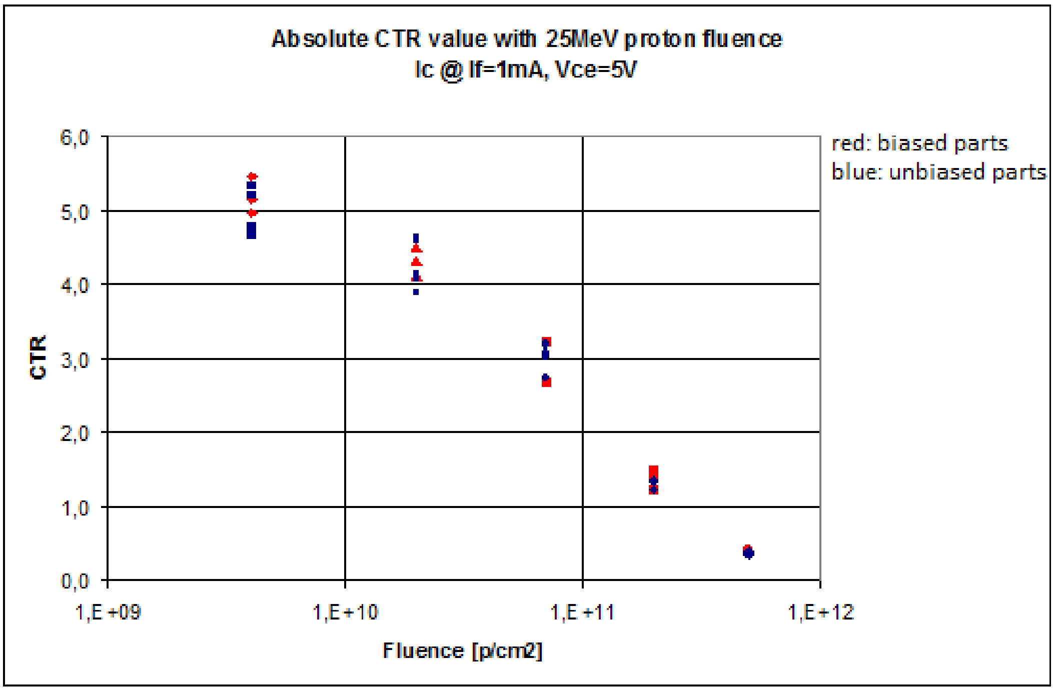

Figure 6: *absolute CTR degradation at 25MeV*

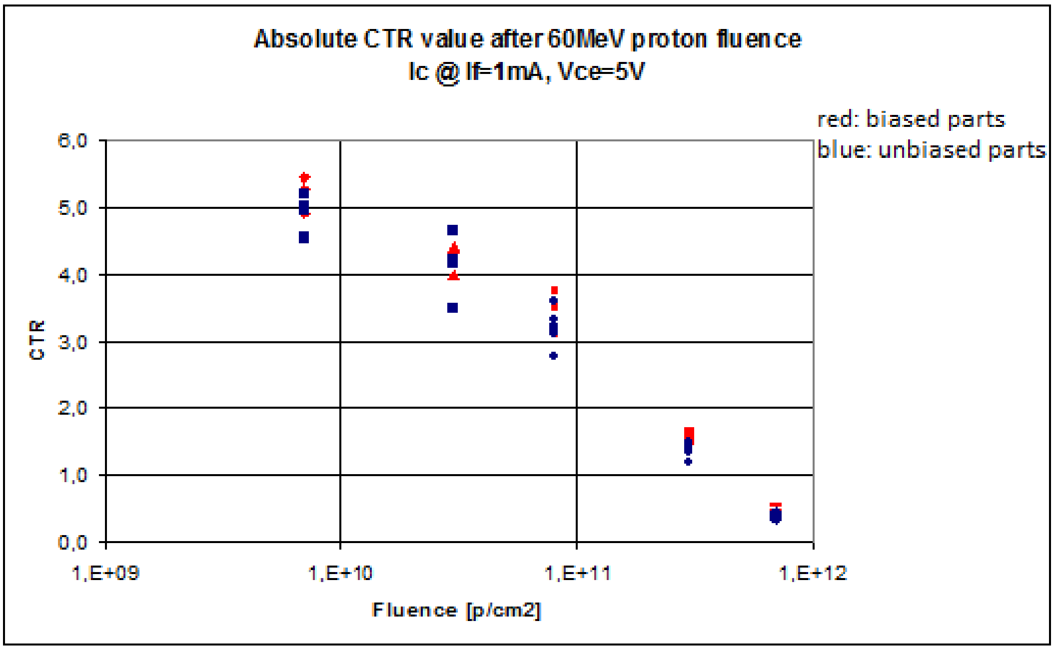

Figure 7: *absolute CTR degradation at 60MeV*

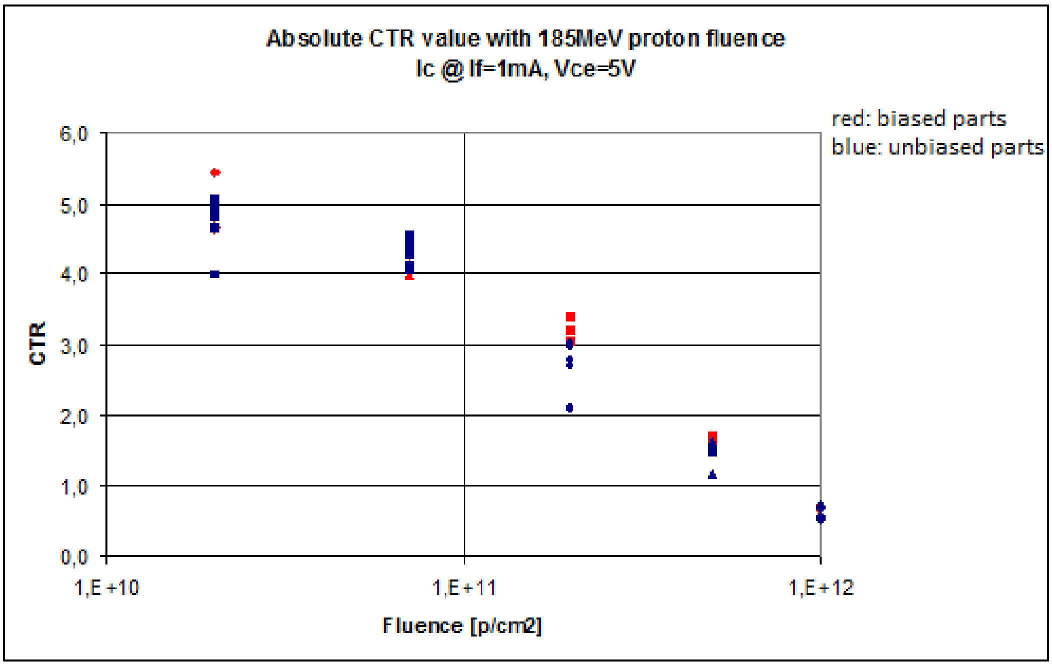

Figure 8: *absolute CTR degradation at 185MeV*

1.3. *Further analyses*

In depth electrical characterizations allow a detailed elaboration of the collected results.
One first consideration regards the degradation of the phototransistor gain.
Figure 9 shows the degradation of the phototransistor gain at 60MeV, with V_{be}=0.7V, considering the average values of the unbiased parts with one standard deviation.

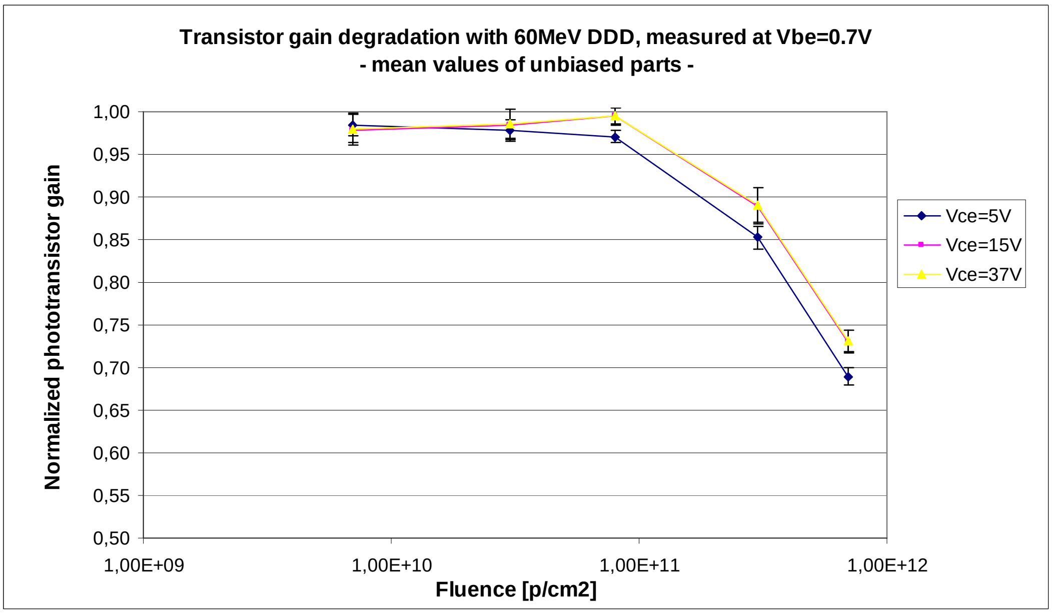

Figure 9: *transistor gain degradation (one standard deviation), V_{be}=0.7V*

Another relevant parameter for evaluating the phototransistor degradation is the increase in dark current after proton irradiation; the absolute increase in dark current lies in the order of tens nA, measured at 20V after 60MeV proton irradiation for each of the five considered fluences. The initial value under the same test conditions is in the order of units of nA.
As far as the dynamic properties of the device are concerned, previous analyses and also parallel ongoing tests proved that the phototransistor response time is in fact improved after proton radiation. So, considering that the optocoupler dynamics are well within the nominal specifications before irradiation, Optoi assumes that the rise and fall times don't represent a critical aspect.

All the analyses on CTR reported in the previous paragraph consider a nominal biasing condition for the LED, i.e. I_f=1mA.
It's interesting to evaluate the optocoupler behaviour as a function of an increase in the LED forward current; such analysis is shown from Figure 10 to Figure 14, considering the reference energy of 60MeV and one unbiased sample per each irradiation step.

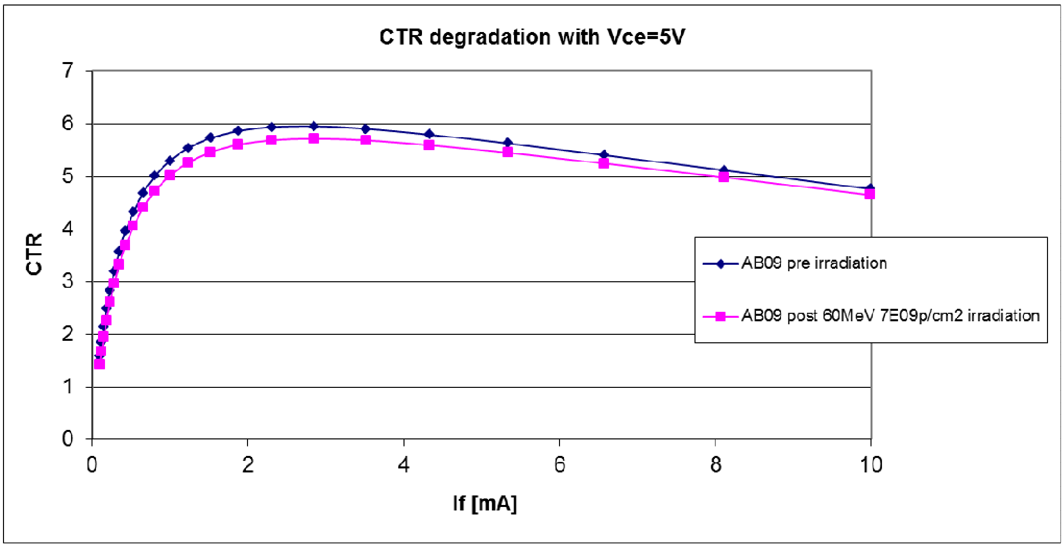

Figure 10: *absolute degradation of CTR of one unbiased sample (AB09) with increasing LED forward current, after 60MeV-7E09p/cm^2 proton irradiation*

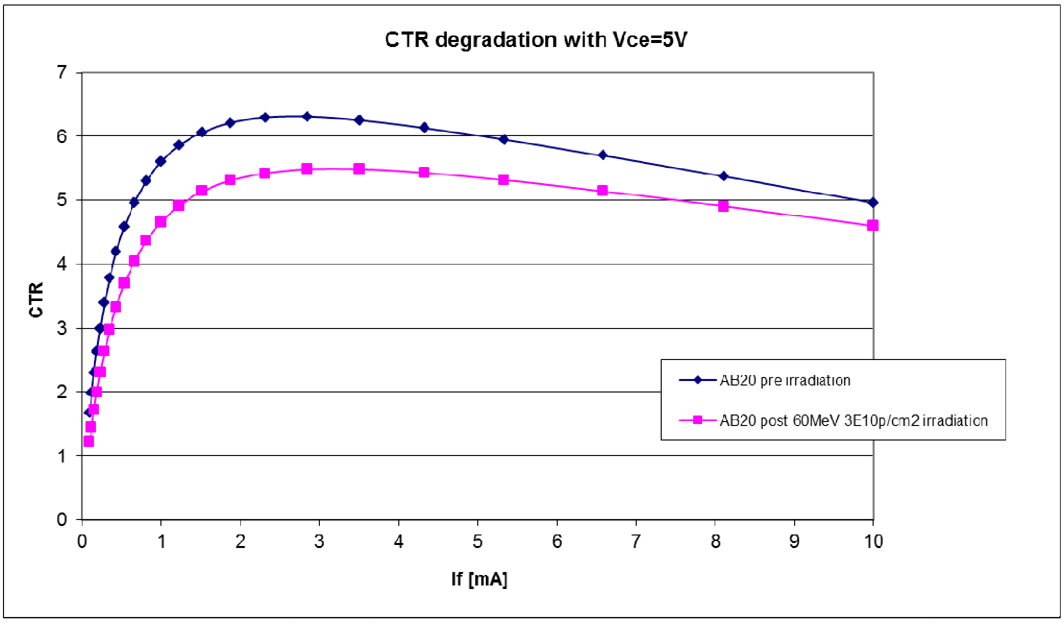

Figure 11: *absolute degradation of CTR of one unbiased sample (AB20) with increasing LED forward current, after 60MeV-3E10p/cm^2 proton irradiation*

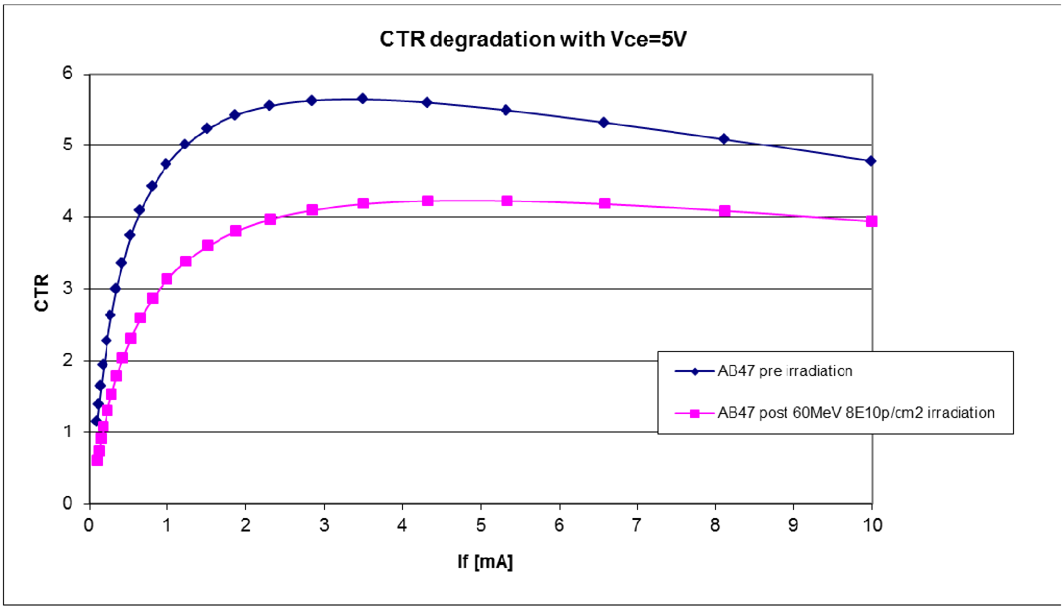

Figure 12: *absolute degradation of CTR of one unbiased sample (AB47) with increasing LED forward current, after 60MeV-8E10p/cm^2 proton irradiation*

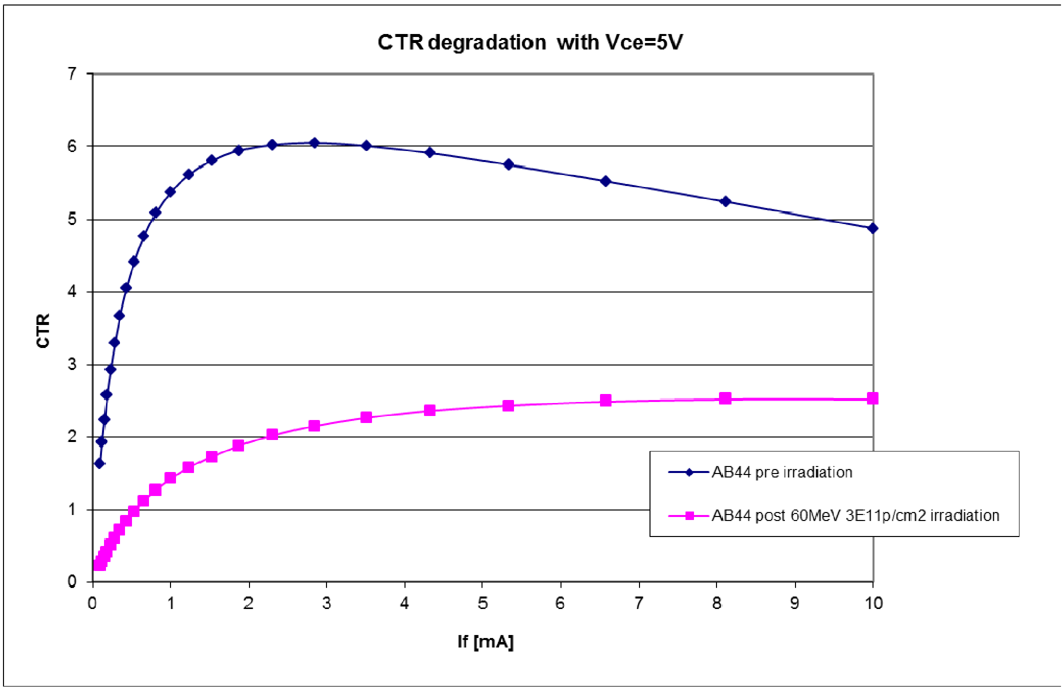

Figure 13: *absolute degradation of CTR of one unbiased sample (AB44) with increasing LED forward current, after 60MeV-3E11p/cm^2 proton irradiation*

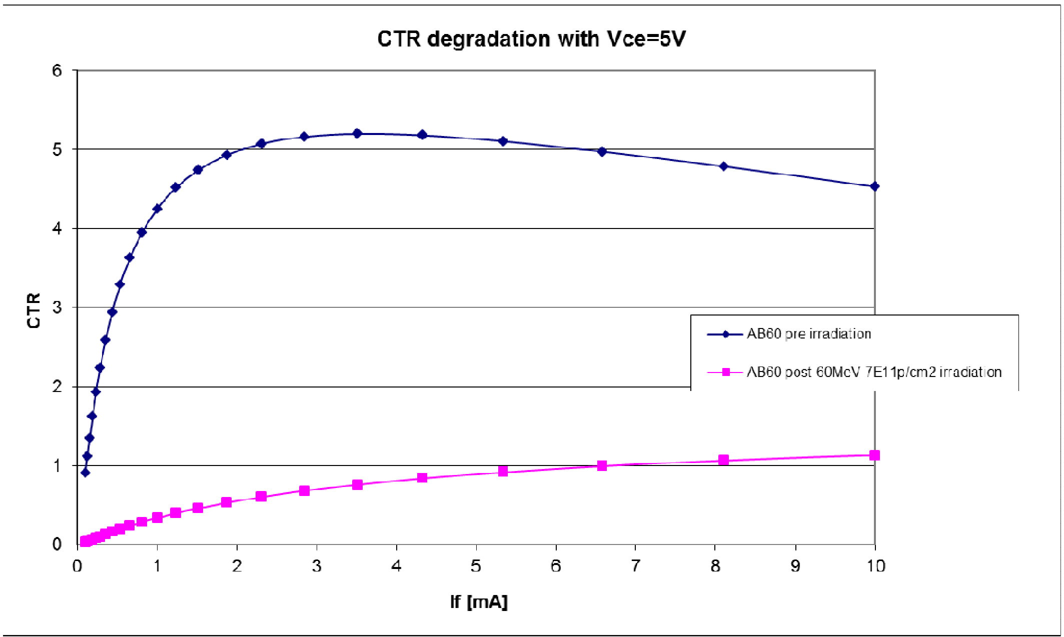

Figure 14: *absolute degradation of CTR of one unbiased sample (AB60) with increasing LED forward current, after 60MeV-7E11p/cm^2 proton irradiation*

The normalized CTR degradation with increasing LED forward current is shown in Figure 15, considering 60MeV-energy and V_{ce}=5V; results are quite similar for the other two biasing conditions of the phototransistor, i.e. V_{ce}=15V and 37V.

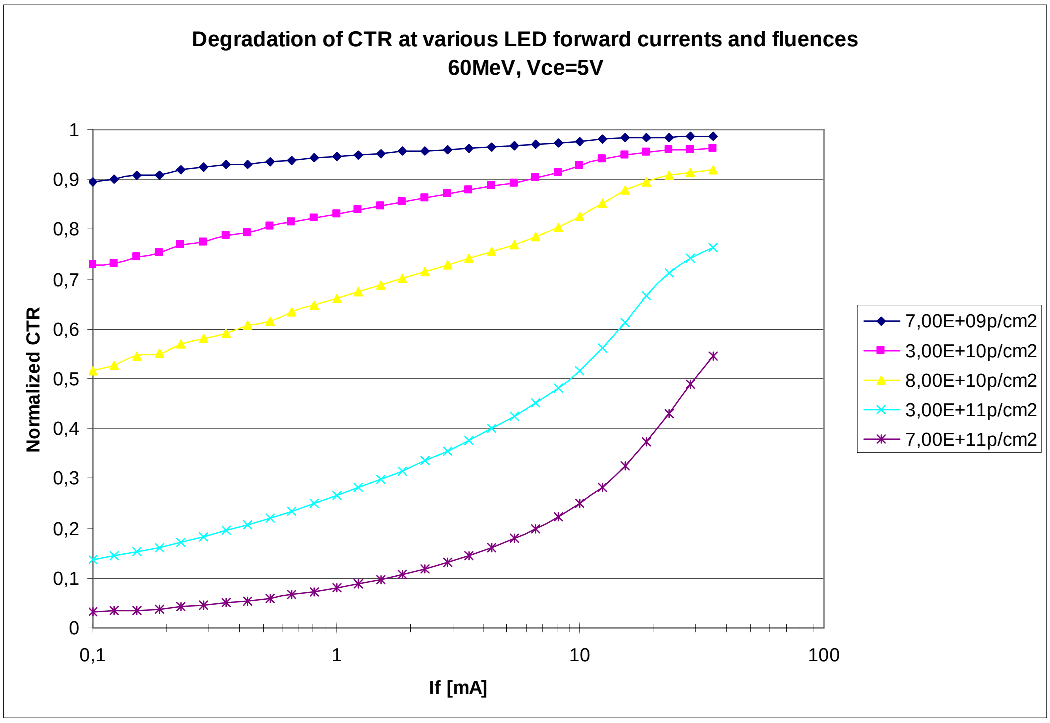

Figure 15: *CTR degradation with increasing LED forward current, considering the reference energy of 60MeV and one unbiased sample per each irradiation step*

The LED forward characteristic, i.e. the I-V curve with positive voltage, is not particularly affected by protons. Figure 16 shows the case of 60MeV-protons with 8E10p/cm2-fluence, on unbiased parts; Figure 17 shows the same trend with a zoom on the area with I_f~10mA.

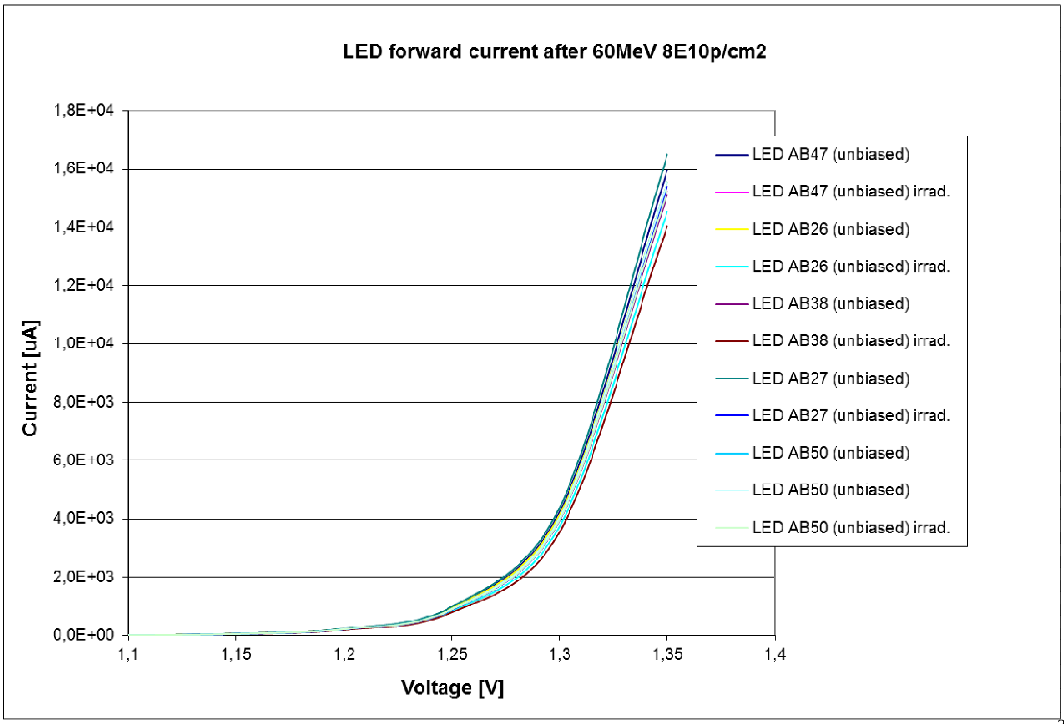

Figure 16: *LED I-V forward characteristics before and after proton irradiation (60MeV, 8E10p/cm²)*

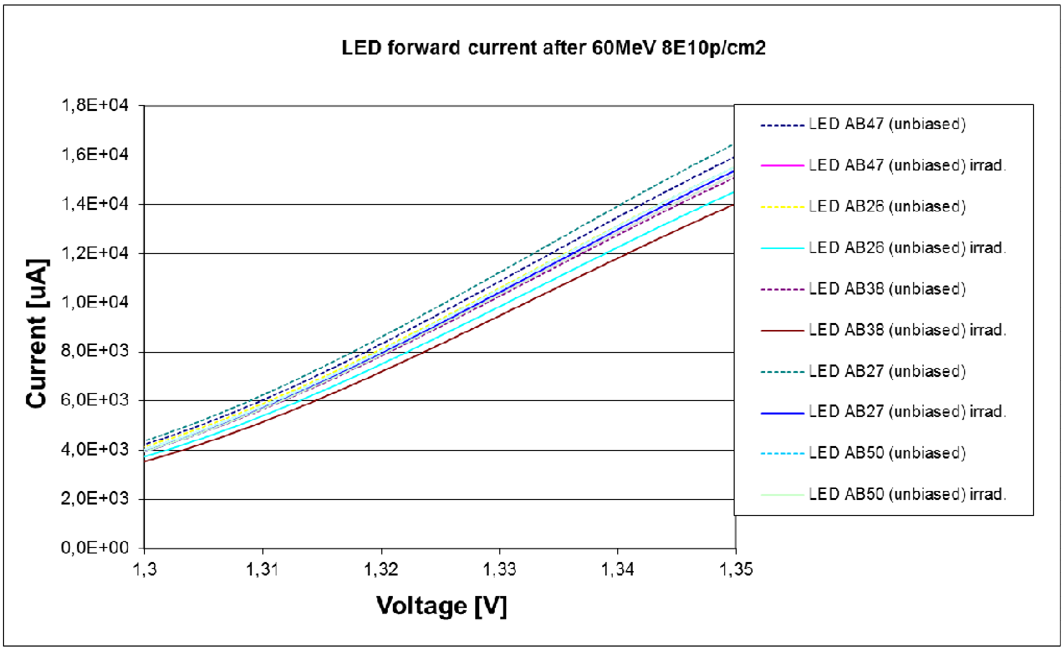

Figure 17: *LED I-V forward characteristics before and after proton irradiation (60MeV, 8E10p/cm2), in the region with If~10mA*

Some samples exposed to proton irradiation have been submitted to an annealing of several days at room temperature, followed by ageing (168-hour at 100°C). A slight recovery on the CTR degradation has been observed on these parts (Figure 18).

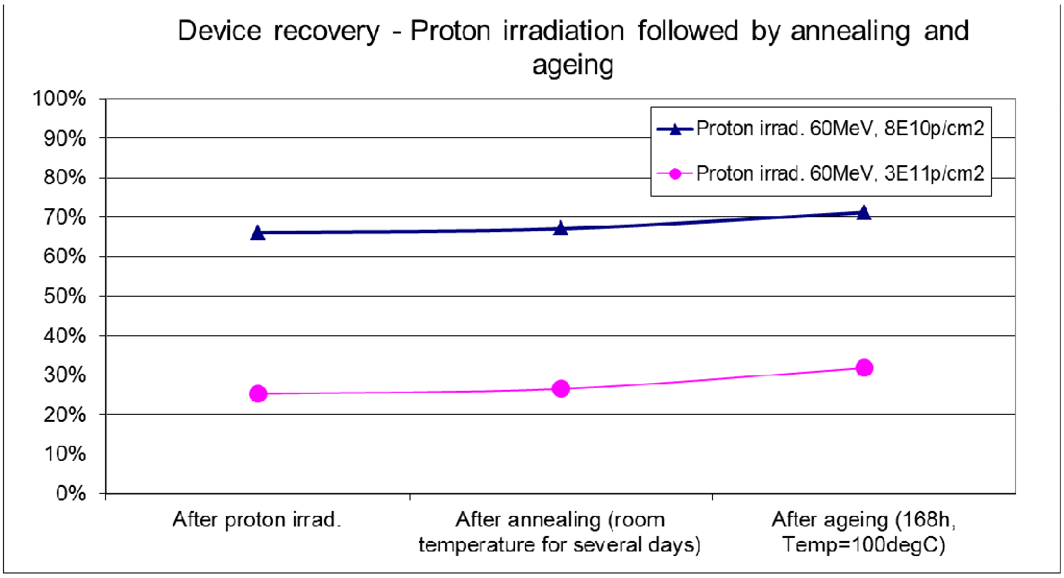

Figure 18: *recovery of optocouplers (indicated with a star in table 2) kept unbiased while irradiated by protons (60MeV, 8E10 and 3E11p/cm2) and subsequently exposed to an annealing of several days at room temperature, followed by ageing (168-hour at 100°C). These devices were tested under nominal conditions, i.e. with* I_f*=1mA,* V_{ce}*=5V*

1.4. CTR degradation versus NIEL

A comparison of the normalized CTR degradation on all unbiased devices irradiated with different proton energies (25MeV, 60MeV, 185MeV) is shown in Figure 19, based on AdvEOTec's elaborations. The NIEL values correspond to Silicon material [RD-1] and the Displacement Damage Dose (DDD) is calculated for all conditions (varying energies and fluences) with respect to the CTR drifts.
The obtained trend is well aligned with the NIEL parameter.

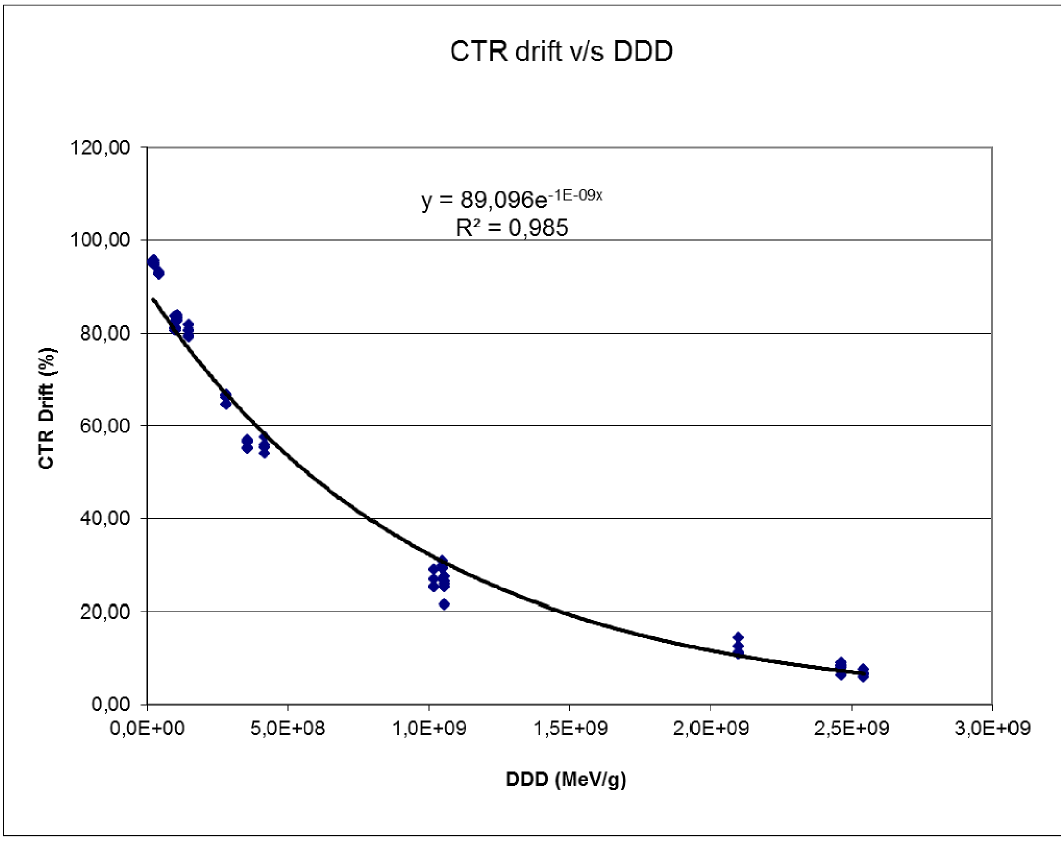

Figure 19: *comparison between the obtained results after DDD and the expected trend according to NIEL modelling – each point represents an unbiased device*

2. Total Ionizing Dose

2.1. General considerations

Tests under gamma rays have been conducted according to the [AD-1] in ESTEC with the support of the Co-60 facility personnel, starting from 13th March 2013. The radiation plan basically followed the original agreements as in Figure 20; the only applied variation was the reach of 150krad(Si) for the high dose tests (360rad/h), regardless of the parallel and slower advance of the low dose rate (36rad/h). Besides, the intermediate measurements were performed leaving a reasonable margin on the value of the overall ionizing doses reported in Figure 20.
The details on the irradiation steps are reported in the radiation test summary included in **Annex 2**.

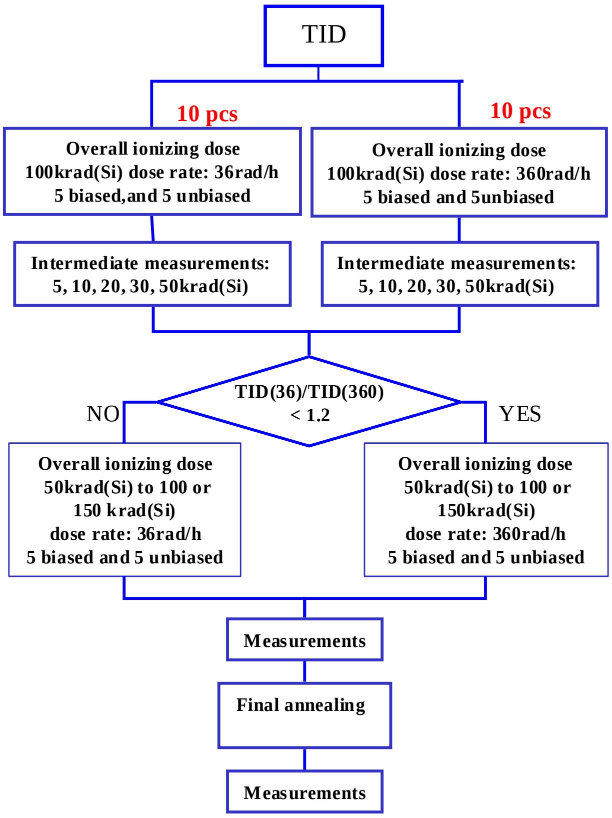

Figure 20: *TID plan as originally defined*

Concerning the device biasing, PCBs similar to those used for proton irradiation tests were used, this time for 5 biased and 5 unbiased devices (Figure 21), with the same specific sockets for the LCC6 type of package and this time with 4mm-banana plugs. A 1MOhm SMD resistor connecting the phototransistor base to the emitter was used, as described for the proton irradiation tests. Biasing conditions during irradiation are the same as for proton irradiation, i.e. I_f=3mA, V_{ce}=5V.
A detailed overview of the tested devices is shown in Table 3 (including the reference devices, either submitted to the same irradiations or just used for the test bench calibration); the underlined devices feature a phototransistor belonging to a different wafer with respect to the majority of the other devices (*ESA121* <u>*W6*</u> *vs. W10*). As for the proton irradiation test campaign, this variation has been distributed "here and there", in order to obtain the best representativeness of such variable.

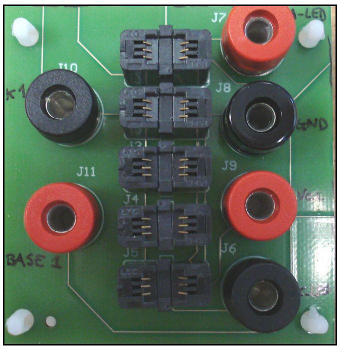

Figure 21: *biasing board used for TID irradiations*

Package	SN	Reference	OPTOI S/N	Test condition	Biasing condition
LCC	#00	OIER10	1	ref	-
LCC	#01	OIER10	AA02	LDR	GND
LCC	#02	OIER10	AA10	LDR	GND
LCC	#03	OIER10	AB04	LDR	GND
LCC	#04	OIER10	AC21	LDR	GND
LCC	#05	OIER10	AC38	LDR	GND
LCC	#06	OIER10	AA03	LDR	If=3mA, Vcc=5V
LCC	#07	OIER10	AB01	LDR	If=3mA, Vcc=5V
LCC	#08	OIER10	AB11	LDR	If=3mA, Vcc=5V
LCC	#09	OIER10	AC22	LDR	If=3mA, Vcc=5V
LCC	#10	OIER10	AC39	LDR	If=3mA, Vcc=5V
LCC	#11	OIER10	AA12	HDR	GND
LCC	#12	OIER10	AA36	HDR	GND
LCC	#13	OIER10	AB15	HDR	GND
LCC	#14	OIER10	AC33	HDR	GND
LCC	#15	OIER10	AC34	HDR	GND
LCC	#16	OIER10	AA16	HDR	If=3mA, Vcc=5V
LCC	#17	OIER10	AB16	HDR	If=3mA, Vcc=5V
LCC	#18	OIER10	AB18	HDR	If=3mA, Vcc=5V
LCC	#19	OIER10	AC43	HDR	If=3mA, Vcc=5V
LCC	#20	OIER10	AC44	HDR	If=3mA, Vcc=5V
LCC	#21	OIER10	AA05	spare	-
LCC	#22	OIER10	AB02	spare	-
LCC	#23	OIER10	AB07	spare	-
LCC	#24	OIER10	AC37	spare	-
TO-5	#00	Isolink OLH249	-	ref	-
TO-5	#05	MII 4N49	#05	LDR	GND
TO-5	#06	MII 4N49	#06	LDR	GND
TO-5	#08	MII 4N49	#08	HDR	GND
TO-5	#11	MII 4N49	#11	HDR	GND

Table 3: *devices submitted to TID (HDR: High Dose Rate; LDR: Low Dose Rate)*

Intermediate measurements were conducted after each irradiation step, in order to monitor the drifts in the following parameters:

- V_{LED}(I_{LED}=1, 2, 5, 10, 20mA)
- Phototransistor I_{cdark} (V_{ce}=2, 4, 6, 8, 10V)
- Phototransistor I_c (I_{LED} =1, 2, 3, 5, 10mA) for two supply voltages (V_{ce} = 5V and V_{ce} =10V), leading to the extrapolation of the CTR

2.2. High dose rate (run 20229)

The irradiation at high dose rate (360rad/h) reached the overall ionizing dose of 169krad(Si) in early April, after a progressive sequence of intermediate measurements. Subsequently, devices were submitted to annealing (24h, ambient temperature), followed by an ageing step (100degC for 168h). This is the usual procedure adopted by ESA, for this kind of radiation campaigns, following the [AD-1].

Results are shown from Figure 22 to Figure 25, considering all biased and unbiased devices, with measurements performed at nominal operating condition, i.e. I_f=1mA, V_{ce}=5V.

5 unbiased and 5 biased devices were submitted to each ionizing dose, whereas the two unbiased reference parts were only included for checking the effect of the growing overall ionizing dose on devices not representing the state of the art among the available radiation hardened components.

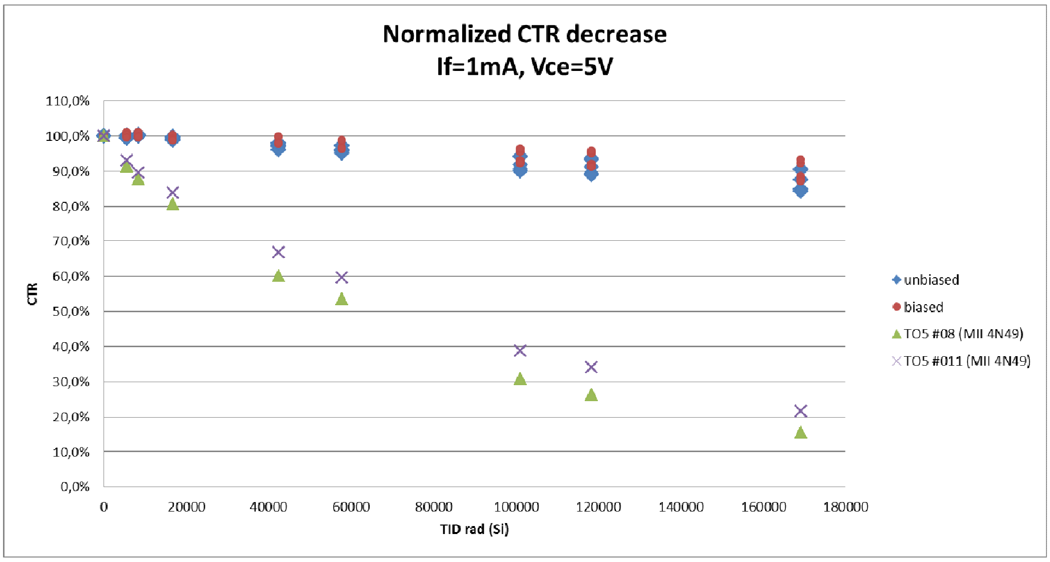

Figure 22: *normalized CTR degradation with TID up to 180krad(Si), at high dose rate (360rad/h)*

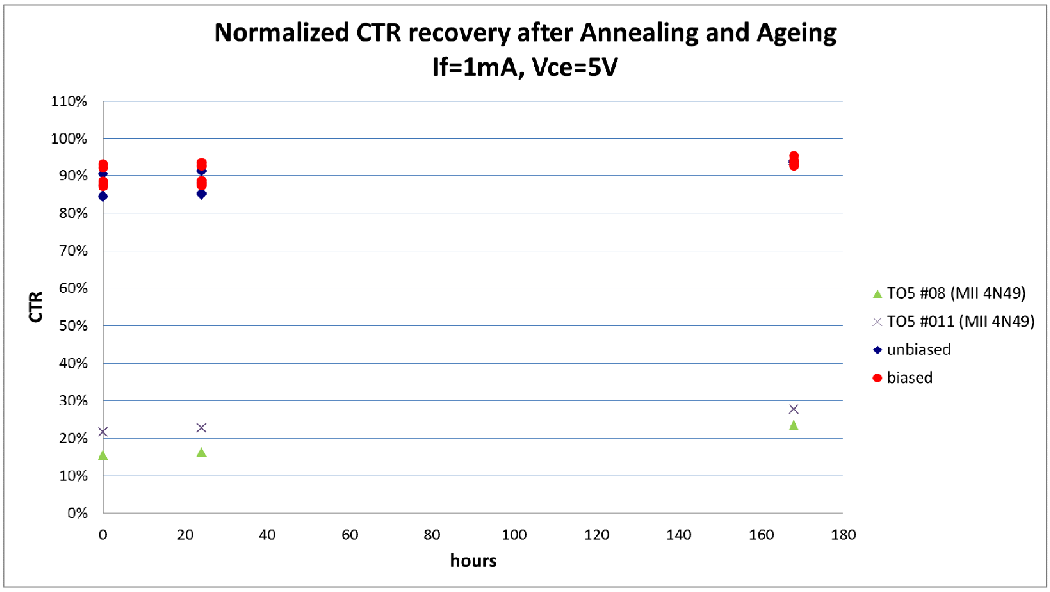

Figure 23: *recovery in the normalized CTR after annealing and ageing, on the devices submitted to high dose rate (360rad/h)*

The variability in the absolute CTR values shown in Figure 24 is mainly due to the usage of phototransistors belonging to different wafers, introducing an intrinsic margin of variation in the CTR even prior to radiation.

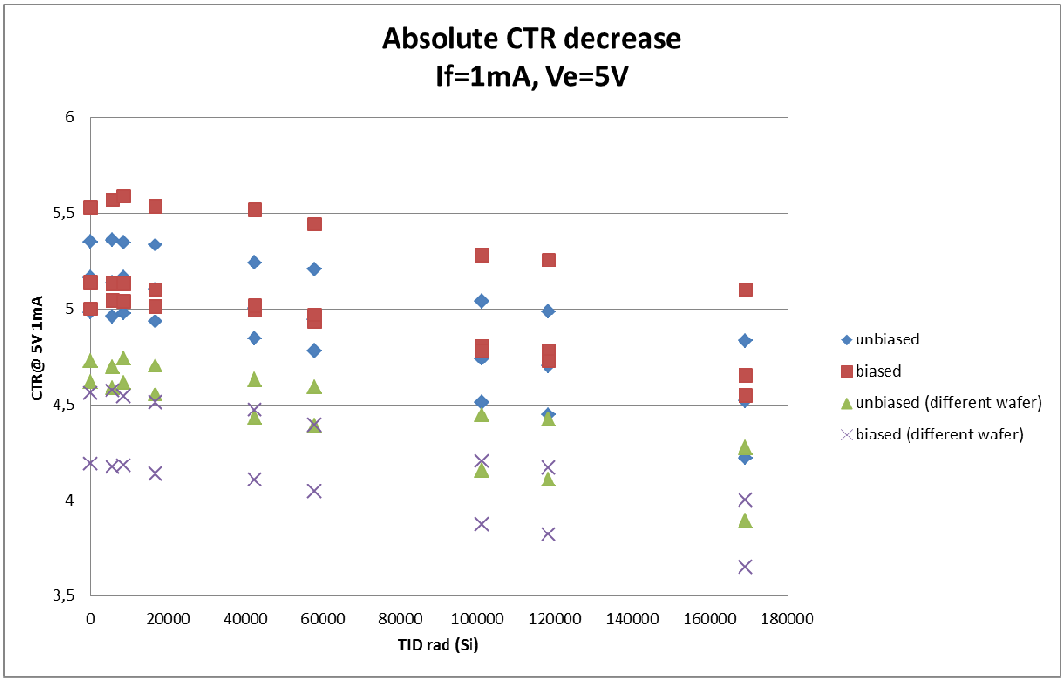

Figure 24: *absolute CTR degradation with TID up to 180krad(Si), at high dose rate (360rad/h)*

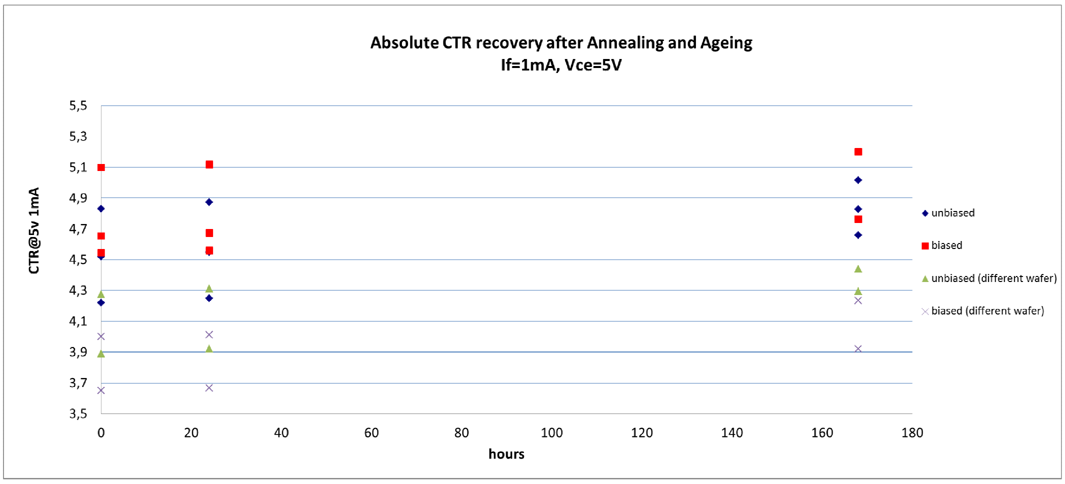

Figure 25: *recovery in the absolute CTR, after annealing and aging, on the devices submitted to high dose rate (360rad/h)*

The same extrapolations have been performed considering a higher biasing condition for the phototransistor, i.e. V_{ce}=10V instead of 5V. The obtained trends are very similar as shown in Figure 26 and Figure 27.

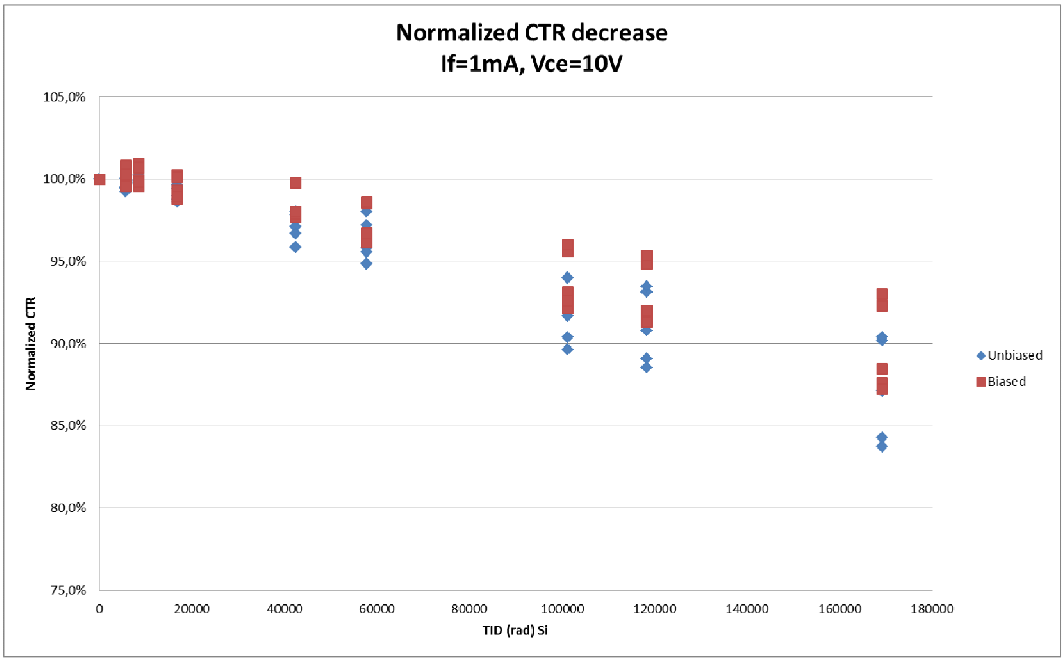

Figure 26: *normalized CTR degradation with TID up to 180krad(Si), at high dose rate (360rad/h)*

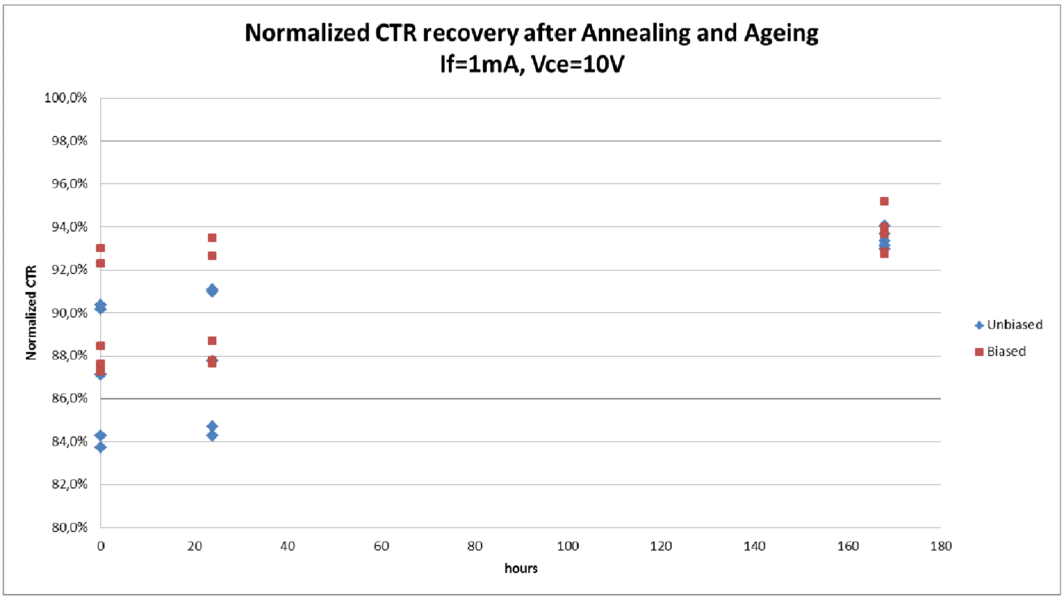

Figure 27: *recovery in the normalized CTR after annealing and aging, for the devices submitted to high dose rate (360rad/h)*

The absolute dark current degradation and the related recovery after annealing and ageing are not shown, because the measured values lie in the range of the instrumentation resolution.
The LED forward current is not affected by gamma radiation; the same consideration was drawn above, in the context of proton irradiation.
The trend in the absolute CTR degradation with various LED forward currents is shown in Figure 28 and Figure 29.

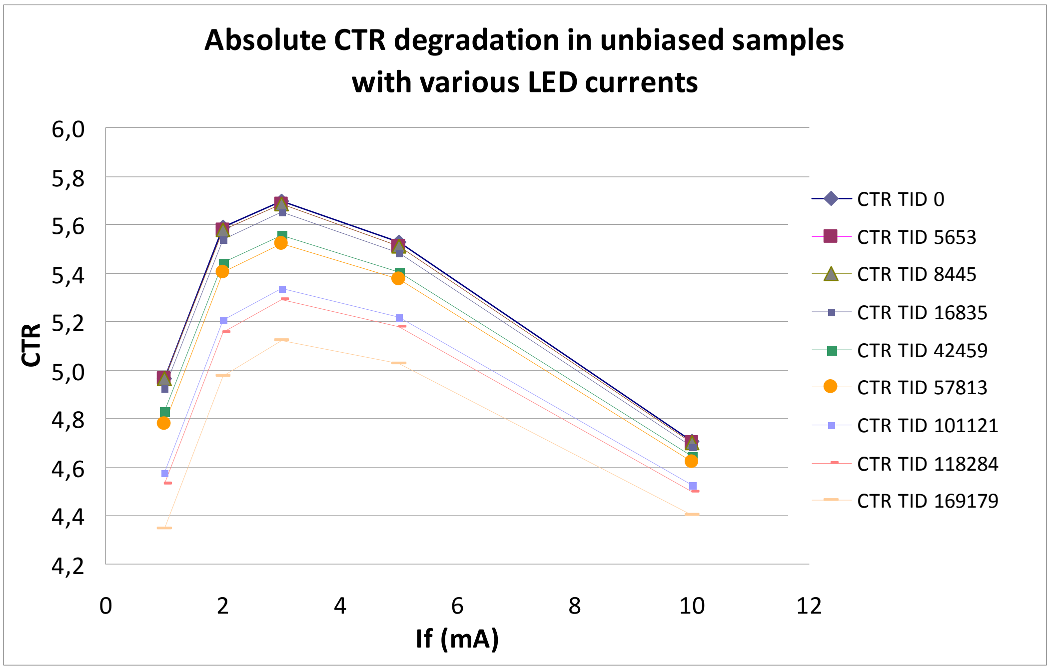

Figure 28: *absolute degradation in CTR vs. LED forward current with increasing overall dose rate, on unbiased samples*

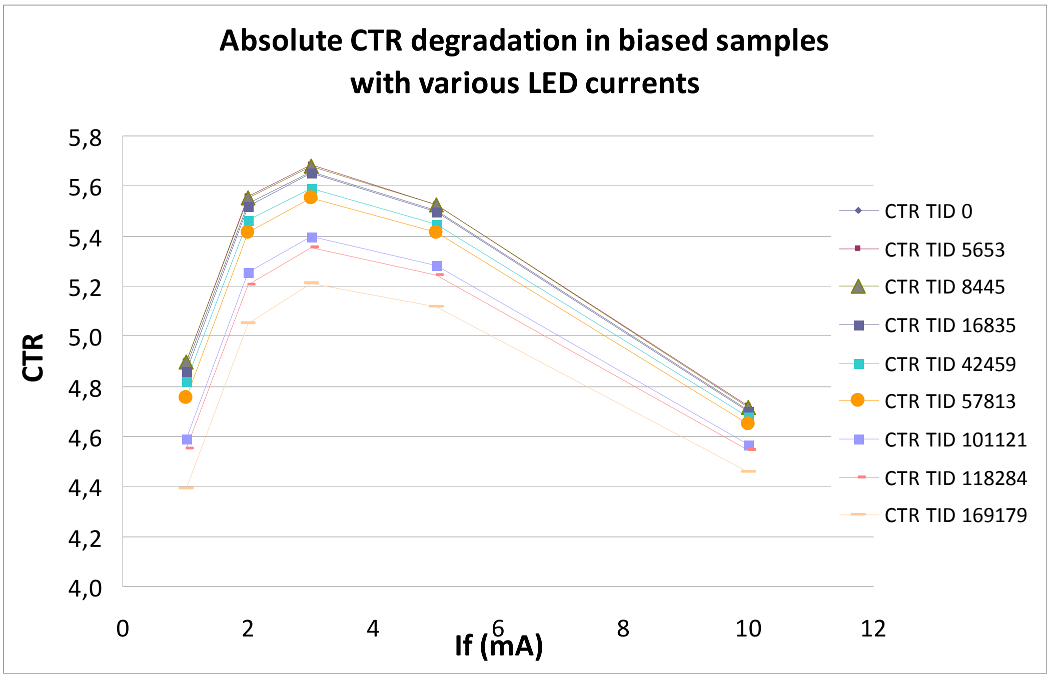

Figure 29: *absolute degradation in CTR vs. LED forward current with increasing overall dose rate, on biased samples*

2.3. Low dose rate (run 20228)

Irradiations at low dose rate reached the overall ionizing dose of 79.6kad(Si); ESA and Optoi decided to avoid the prosecution of this campaign considering its strong similarity to the case of high dose rate.
Results are shown from Figure 30 to Figure 33.
Curves with V_{ce}=10V follow a similar trend.

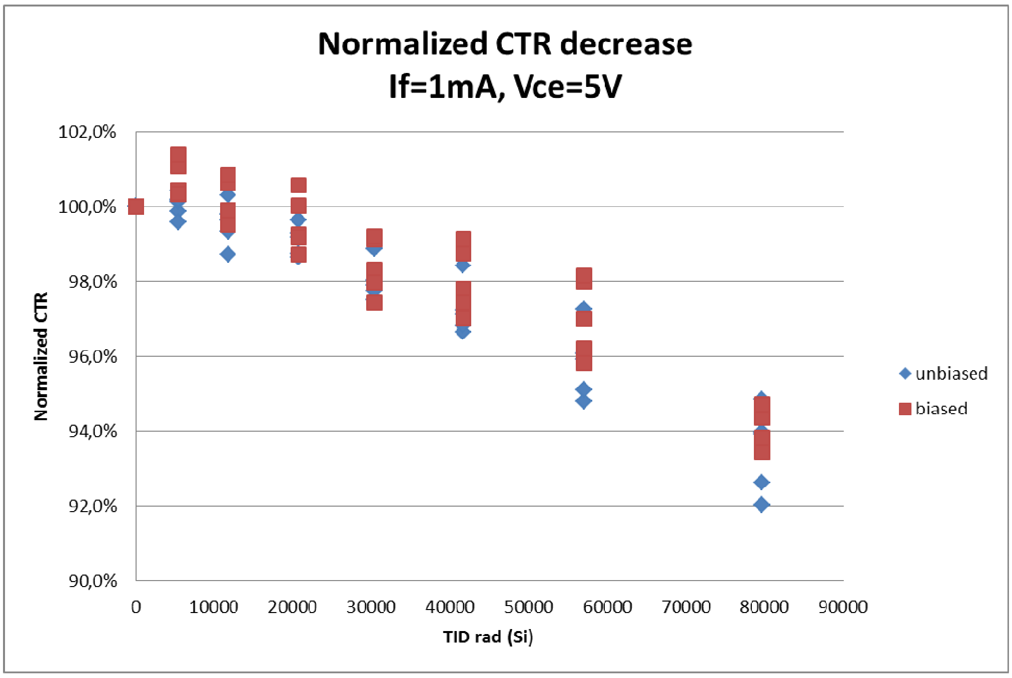

Figure 30: *normalized CTR degradation with TID up to 79.6 krad(Si), at low dose rate (36rad/h)*

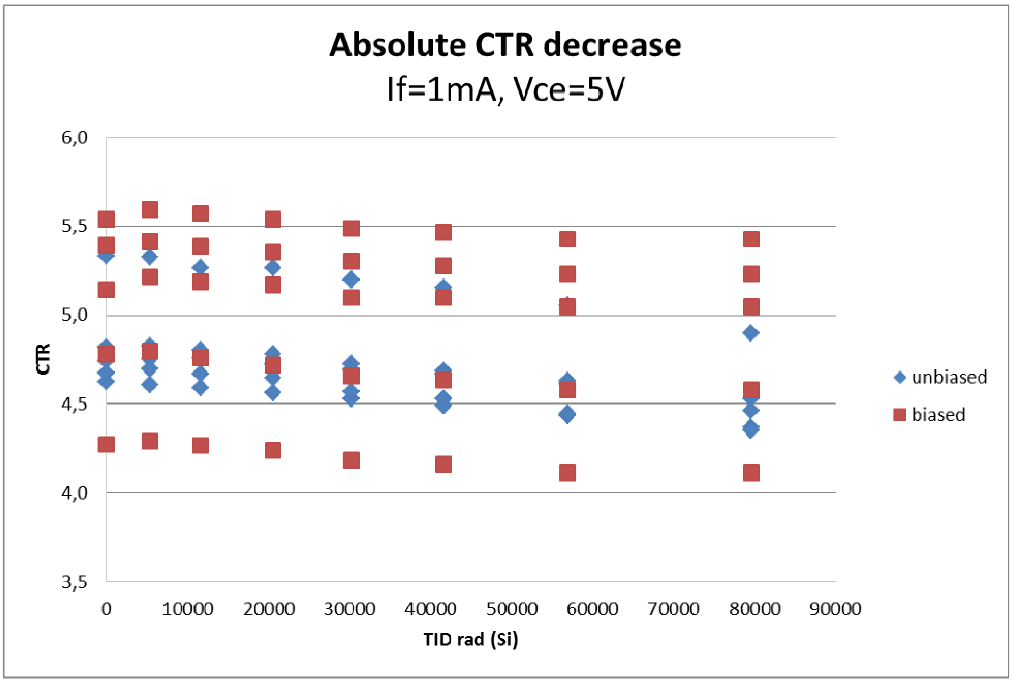

Figure 31: *absolute CTR degradation with TID up to 79.6 krad(Si), at low dose rate (36rad/h)*

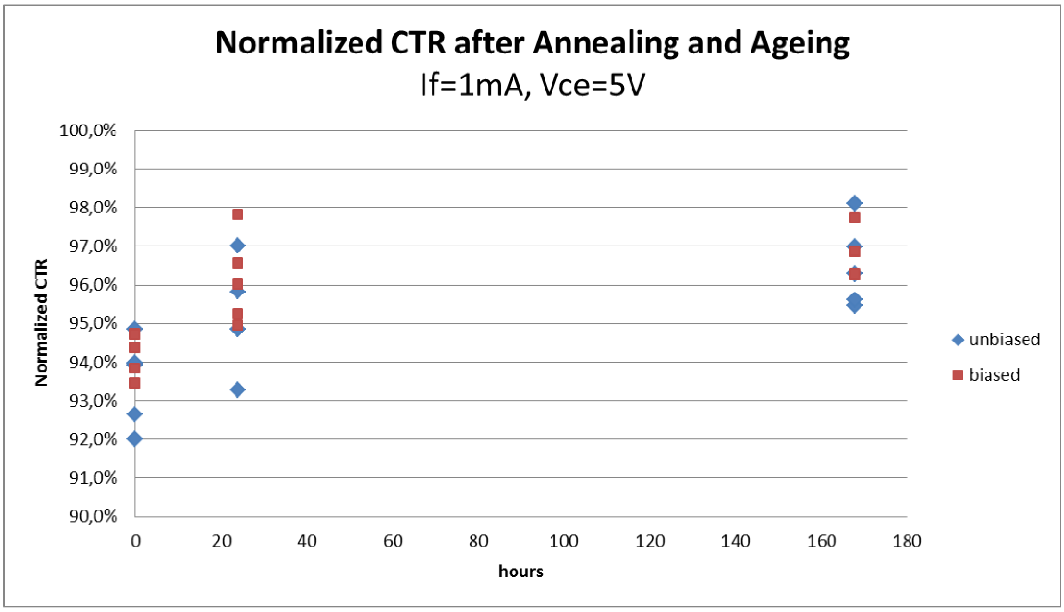

Figure 32: *recovery in the normalized CTR after annealing and aging, on the devices submitted to low dose rate (36rad/h)*

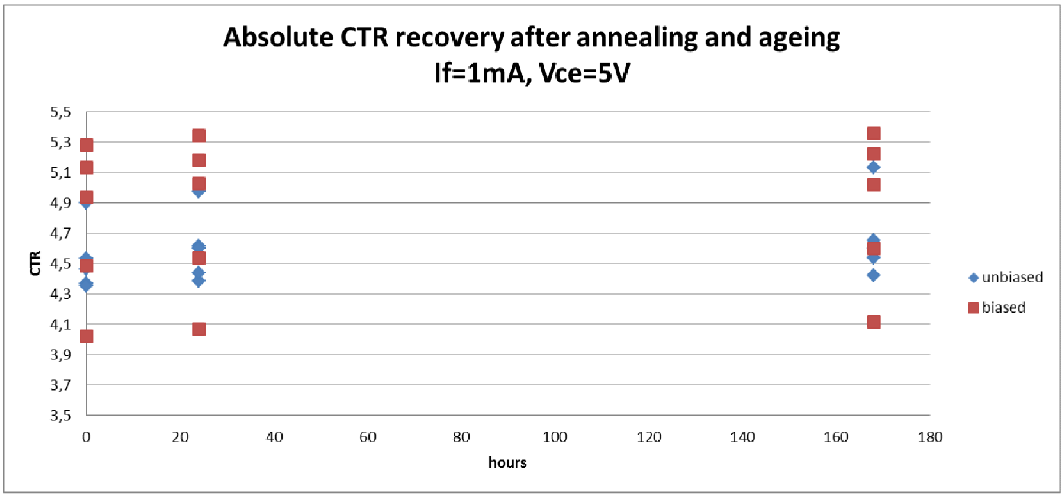

Figure 33: *recovery in the normalized CTR after annealing and aging, on the devices submitted to low dose rate (36rad/h)*

The absolute dark current degradation is negligible.
Similarly to the high dose rate, the LED forward current is not particularly affected by the gamma radiation.
The trend in the absolute CTR degradation with various LED forward currents is shown in Figure 34 and Figure 35.

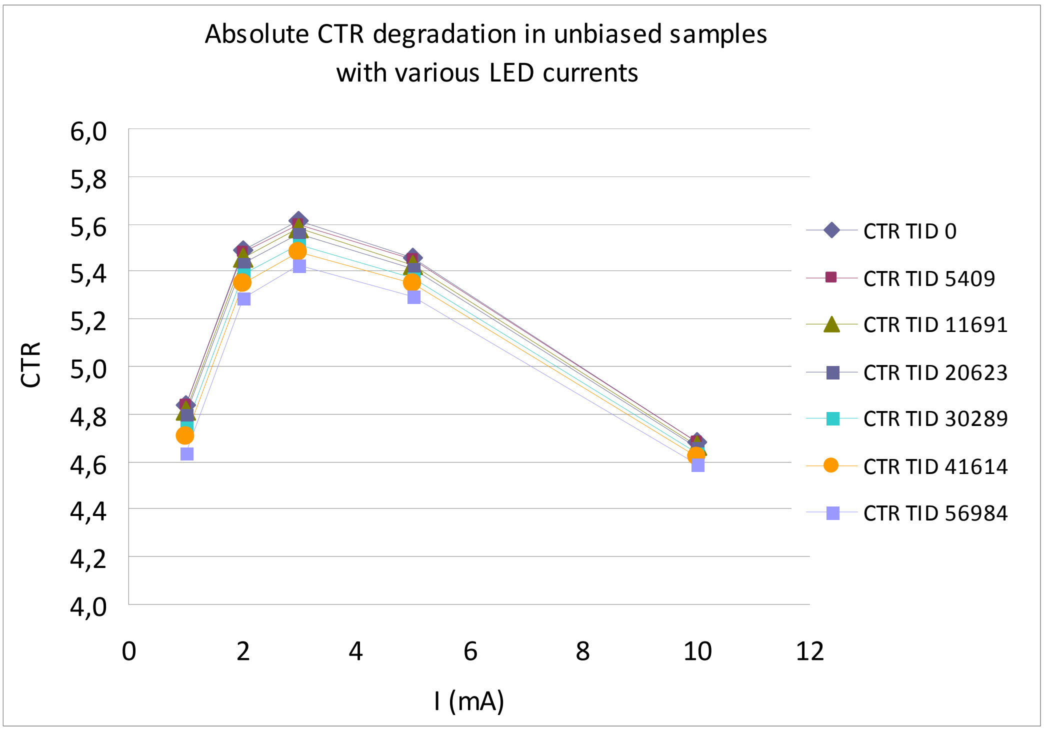

Figure 34: *absolute degradation in CTR vs. LED forward current with increasing overall dose rate, on unbiased samples*

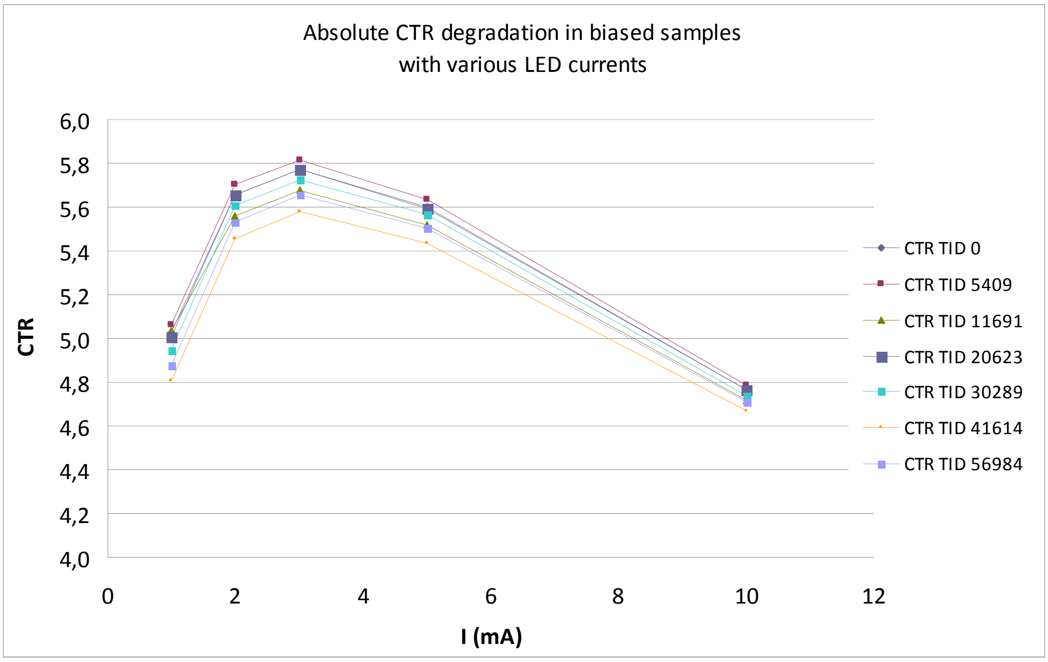

Figure 35: *absolute degradation in CTR vs. LED forward current with increasing overall dose rate, on biased samples*

Conclusion

Optoi's feeling on radiation results is quite optimistic.
In fact, under **proton irradiation** the detected degradation in the CTR is comparable to other optocoupler brands, if its normalized value is considered. The absolute value of CTR might be considered lower than some other commercially available devices, since the start of the radiation campaign; this is intrinsically due to the optocoupler architecture and coupling between the two components, i.e. LED and phototransistor. In principle, improvements are possible through a more efficient device architecture.

The degradation under **gamma rays** is less remarkable if compared to the proton irradiation. This is in agreement with Optoi's expectations, based on previous analyses and estimations. The obtained results are well positioned with respect to the competition.

In the framework of the proton irradiation testing campaign, Optoi took the chance to irradiate other optocouplers hosting a different type of phototransistor, and also standalone phototransistor arrays.
These **additional irradiations** allowed indirect observations and they confirmed the overall quality in the documented achievements.

Attachments

Annex 1 – details of the proton irradiations

Subject:	**Report on the irradiation for Optoi on April 10, 2013**
To:	Matteo Bregoli (Optoi)
From:	Reint Ostendorf (KVI)
Date:	May 2nd, 2013

Beam energy

The nominal energy of the proton beam extracted from the cyclotron was 190 MeV. After passing through the scatterers (a first homogeneous Pb foil of 1.44 mm and a second parabolically shaped W foil of 0.9 mm) and 3.45 m of air the nominal beam energy at the position of the component to be irradiated was approximately 184 MeV. We also performed irradiations with a nominal beam energy of 60 MeV, using a degrader setting of 91.5 mm of aluminium. The quantity of aluminium used to degrade the beam energy was based both on earlier energy measurements with our range telescope and on ion-stopping-and-range tables.

Field size and homogeneity

The field size at the DUT was defined by a 100 mm diameter collimator that was positioned upstream of the KVI beam degrader. The dose distribution was measured as the light output distribution of a LANEX (Kodak) scintillating screen. From Monte Carlo calculations we know that particles scattered from a 70 mm diameter collimator create a ~3% contribution to the dose, which is nearly homogeneous. It is therefore concluded that the homogeneity of the dose distribution reflects the homogeneity of the flux distribution. We found that using this 100 mm diameter collimator the field at the location of the device under test (DUT) had a better than 10% homogeneity in dose over an area larger than 83 mm in diameter (see figures 1 and 2 in table 3).

Flux calibration procedure

The intensity of the beam is monitored with our "Beam Intensity Monitor" (BIM) that is an ionisation chamber positioned in the beam at 170 cm downstream of the exit foil. The current from the ionisation chamber is transformed in a pulse train, where the rate of the pulses is proportional to the current from the chamber. As a result, every pulse or "Monitor Unit" (MU) as we have named them represents an amount of beam or similarly an amount of protons per cm^2.

Previously we have performed irradiations using the same primary beam, scatter foils and degrader. In that irradiation we checked the flux calibration obtained using a small plastic scintillation detector with a measurement using a calibrated dosimeter, a Farmer chamber. Those results matched well with simulations.

For this irradiation we therefore obtained the flux calibration only by a measurement using this calibrated dosimeter. The measured dose was transformed into a flux using both earlier measured flux/dose data as well as simulation data. In this way we obtained the fluence (#p cm^{-2}) per MU (Monitor Unit of the Beam Intensity Monitor) at the DUT position for the KVI degrader for the 4 different energies and their associated settings of the degrader. The calibration coefficients are given in Table 1. The statistical accuracy of these values is better than 1%. The systematic errors are estimated to be smaller than 10% on the basis of dose measurements, earlier measurements for different collimator sizes and Aluminium activation analysis.

Table 1: Flux calibration factors for the irradiations.

Energy [MeV]	Flux calibration [#p cm^{-2} MU^{-1}]
184	2336
60	1706

Irradiations

A series of 11 irradiations was performed. For each irradiation run we list the run number, a sample ID, the energy at DUT, the fluence, the duration and the average flux in table 2.

Table 2: List of irradiations.

Run #	Sample ID	Energy [MeV]	Fluence [#p cm^{-2}]	Duration [s]	Flux [#p $cm^{-2}s^{-1}$]
1	optoi1	184	2.00E+10	184.9	1.08E+08
2	optoi2	184	7.00E+10	336.5	2.08E+08
3	optoi3	184	2.00E+11	670.7	2.98E+08
4	optoi4	184	5.00E+11	1383.5	3.61E+08
5	optoi5	184	1.00E+12	1739.6	5.75E+08
6	optoi6	60	7.00E+09	35.4	1.98E+08
7	optoi-X	60	5.00E+10	234.7	2.13E+08
8	optoi7	60	3.00E+10	140.1	2.14E+08
9	optoi8	60	8.00E+10	374.1	2.14E+08
10	optoi9	60	3.00E+11	933.6	3.21E+08
11	optoi10	60	7.00E+11	1839.8	3.80E+08

Table 3: The horizontal profiles of the irradiation field are presented for both energies used in the irradiation runs: 184 MeV and 60 MeV. The horizontal axis is in units of CCD-pixels, 100 pixels correspond to 2.381 cm. The vertical axis is proportional to the amount of light produced in the LANEX screen.

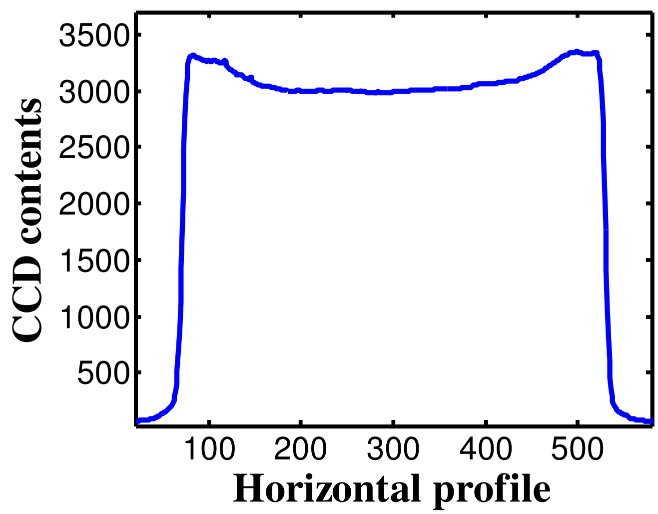

Figure 1: 184 MeV

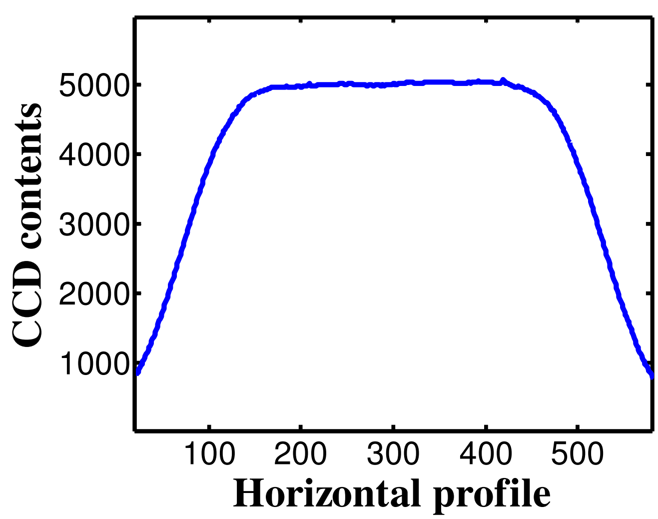

Figure 2: 60 MeV

Details of the high energy DDD campaign

ESA								IF QSX1=4		QSX1 setting corrected						
sample			Fluence	flux	duration	duration	Calibration	Beam current		QSX1 settin	MMU set	BIM rate		Act.time	Mean.flux	Act.fluence
ESA	Energy	Degrader	#p/cm2	#p/cm2/s	s	min	#protons/cm^2/MU	nA	MMU		MMU	Hz	QSX1 cor factor			
optoi1	184	0	2,00E+10	1,00E+08	2,00E+02	3,33	2336,41	1,09E+01	8,560	4	8,560	4,291E+04	1	184,892	1,08E+08	2,00E+10
optoi2	184	0	7,00E+10	1,00E+08	7,00E+02	11,67	2336,41	1,09E+01	29,961	4	29,961	4,291E+04	1	336,511	2,08E+08	7,00E+10
optoi3	184	0	2,00E+11	3,00E+08	6,67E+02	11,11	2336,41	3,28E+01	85,601	4	85,601	1,285E+05	1	670,709	2,98E+08	2,00E+11
optoi4	184	0	5,00E+11	4,00E+08	1,25E+03	20,83	2336,41	4,37E+01	214,004	4	214,004	1,713E+05	1	1383,518	3,61E+08	5,00E+11
optoi5	184	0	1,00E+12	4,00E+08	2,50E+03	41,67	2336,41	4,37E+01	428,007	4	428,007	1,713E+05	1	1739,577	5,75E+08	1,00E+12
optoi6	60	91,5	7,00E+09	2,00E+08	3,50E+01	0,58	1705,58	2,99E+01	4,104	4	4,104	1,174E+05	1	35,428	1,98E+08	7,00E+09
optoi7	60	91,5	3,00E+10	2,00E+08	1,50E+02	2,50	1705,58	2,99E+01	17,589	4	17,589	1,174E+05	1	140,118	2,14E+08	3,00E+10
optoi8	60	91,5	8,00E+10	2,00E+08	4,00E+02	6,67	1705,58	2,99E+01	46,905	4	46,905	1,174E+05	1	374,09	2,14E+08	8,00E+10
optoi9	60	91,5	3,00E+11	3,00E+08	1,00E+03	16,67	1705,58	4,49E+01	175,893	4	175,893	1,760E+05	1	933,647	3,21E+08	3,00E+11
optoi10	60	91,5	7,00E+11	3,50E+08	2,00E+03	33,33	1705,58	5,23E+01	410,418	4	410,418	2,053E+05	1	1839,776	3,80E+08	7,00E+11

Subject:	**Report on the irradiation for Optoi on April 11, 2013**
To:	Matteo Bregoli (Optoi)
From:	Reint Ostendorf, KVI
Date:	May 2nd, 2013

Beam energy

The nominal energy of the proton beam extracted from the cyclotron was 40 MeV. A later, more precise estimate of the beam energy, based on magnet settings, was 38.5 MeV. In this irradiation an exact knowledge of the beam energy was very important. Therefore we measured the energy of the beam at the DUT position using our "multi-leaf-faraday-cup". This device is in essence a stack of 64 aluminium plates all with a thickness of 0.5 mm. The aluminium plates are electrically insulated from each other by 25 µm thick kapton sheets. Ions in the beam that are stopped in this stack deposit their charge in the plate where they are stopped. All currents from the 64 aluminium plates are measured and their profile yields the range of the ions. From the measured range we calculate the energy of the ions using stopping power and range tables. In this way we determined the beam energy, at the DUT position, to be 28.9 ± 0.4 MeV. Other energies were achieved by degrading the beam with our aluminium degrader. Degrading with multiples of 1 mm aluminium lead to the energies listed in table 1. The degrader setting of 3.4 mm aluminium was added because this is the setting that produces 10 MeV protons at DUT. The error bars are of statistical nature only, i.e., they were derived from the accuracy the range could be measured with, which was typically at the level of 0.1 mm of aluminium. The error bars do not reflect the uncertainty (roughly 1%) in the knowledge of the stopping powers and ranges.
A GEANT4 simulation was performed to reproduce the energy at DUT. This simulation was based on the reported beam energy of 38.5 MeV and also included the 0.34 mm thick scatter foil, the collimators in the line, the ionisation chamber and the surrounding air. The simulation predicts the average proton energy at DUT to be 28.74 MeV, which is consistent with the measured value of 28.9 ± 0.4 MeV.

Table 1: Ranges in aluminium of the protons and their energies vs. the degrader setting.

Degrader Setting [mm]	Range in Al [g/cm^2]	Energy [MeV]
0	1.10 ± 0.03	28.9 ± 0.4
1.0	0.83 ± 0.03	24.7 ± 0.5
2.0	0.56 ± 0.03	19.7 ± 0.6
3.0	0.29 ± 0.03	13.6 ± 0.9
3.4	0.18 ± 0.03	10.3 ± 1.1

Field size and homogeneity

The device to be tested was set up at 345 cm downstream of the exit foil, where the beam leaves the vacuum in the beam transport lines. The irradiation field was defined by a 100 mm diameter collimator that was positioned upstream of the KVI beam degrader. This collimator was made of brass and having been designed to be able to stop protons at 190 MeV it was 45 mm thick. A scatter foil with a thickness of 0.34 mm of Pb was positioned 45 cm downstream of the exit foil. The dose distribution was measured as the light output distribution of a LANEX (Kodak) scintillating screen. From Monte Carlo calculations we know that particles scattered from a 70 mm diameter collimator create a ~3% contribution to the dose, which is nearly homogeneous. It is therefore concluded that the homogeneity of the dose distribution reflects the homogeneity of the flux distribution. We found that using this 100 mm diameter collimator the field at the location of the device under test (DUT) had a better than 10% homogeneity in dose over an area larger than 65 mm in diameter at 10 MeV and larger than 74 mm at all other energies (see figures 1 – 5 in table 3).

Flux calibration procedure

The intensity of the beam is monitored with our "Beam Intensity Monitor" (BIM) that is an ionisation chamber positioned in the beam at 170 cm downstream of the exit foil. The current from the ionisation chamber is transformed in a pulse train, where the rate of the pulses is proportional to the current from the chamber. As a result, every pulse or "Monitor Unit" (MU) as we have named them represents an amount of beam or similarly an amount of protons per cm^2.

We have established that we can measure the flux using a small plastic scintillation detector of 1 cm diameter placed at the position of the DUT. In earlier measurements we found by means of coincidence measurements that protons, as compared to neutrons, are responsible for ≥ 99.5% of the count rate in this small detector. We also ascertained that the effective area of the small detector is ≥ 98% of its geometrical area.

This scintillation detector was used to obtain the fluence (#p cm^{-2}) per MU (Monitor Unit of the Beam Intensity Monitor) at the DUT position. The flux calibration values are presented in table 1. The statistical accuracy of these values is better than 1%. The systematic errors are estimated to be smaller than 10% on the basis of dose measurements, earlier measurements for different collimator sizes and aluminium activation analysis.

As an independent check of the flux calibration we also measured the dose deposited in our calibrated dosimeter, a Farmer chamber. The measured flux over dose ratio reproduced the earlier measurements in the previous irradiations at the same (primary) energy well.

Table 2: Calibration factors for the irradiations.

Energy [MeV]	Degrader Setting [mm]	Calibration [#p cm^{-2} MU^{-1}]
28.9	0.0	509
24.7	1.0	505
19.7	2.0	497
13.6	3.0	485
10.3	3.4	452

Irradiations

A series of 5 irradiations was performed. For each irradiation run we list the run number, the sample ID, the energy, the fluence, the duration, and the average flux in table 3.

Table 3: List of irradiations.

Run #	Sample ID	Energy [MeV]	Fluence [#p cm^{-2}]	Duration [s]	Flux [#p $cm^{-2}s^{-1}$]
1	optoi1	24.7	4.00E+09	90.1	4.44E+07
2	optoi2	24.7	2.00E+10	410.4	4.87E+07
3	optoi3	24.7	7.00E+10	700.1	1.00E+08
4	optoi4	24.7	2.00E+11	407.1	4.91E+08
5	optoi5	24.7	5.00E+11	983.2	5.09E+08

Table 4: The horizontal profiles of the irradiation fields are presented for several degrader settings. The intensity distribution was not measured with the degrader setting of 3.4 mm of aluminium. Therefore we present the distribution with the 3.5 mm degrader setting. The horizontal axis is in units of CCD-pixels, 100 pixels correspond to 2.381 cm. The vertical axis is proportional to the amount of light produced in the LANEX screen.

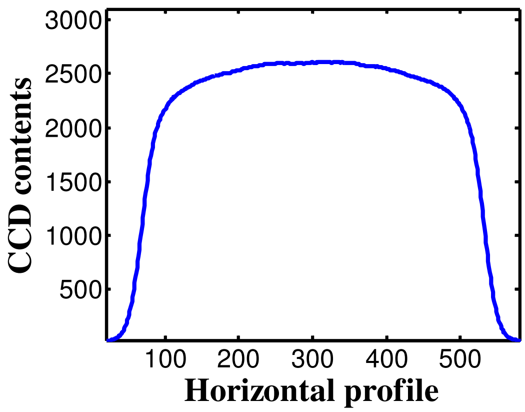

Figure 1: no degrader: 28.9 MeV

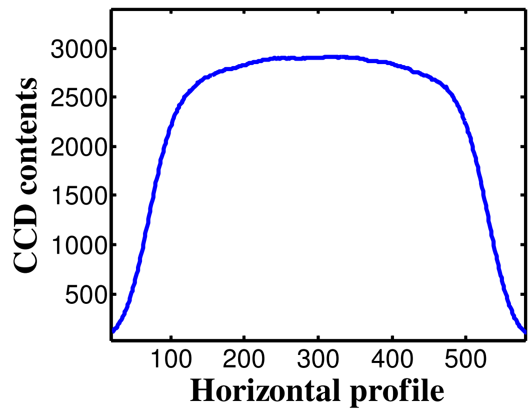

Figure 2: 1 mm degrader: 24.7 MeV

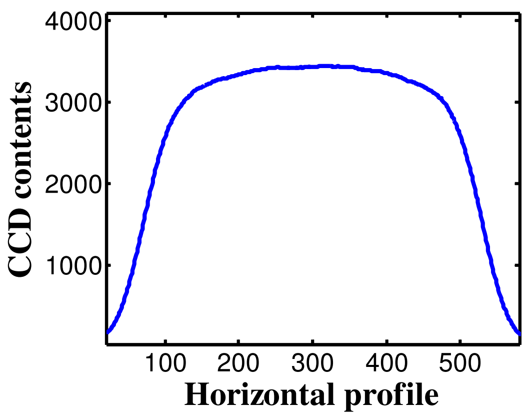

Figure 3: 2 mm degrader: 19.7 MeV

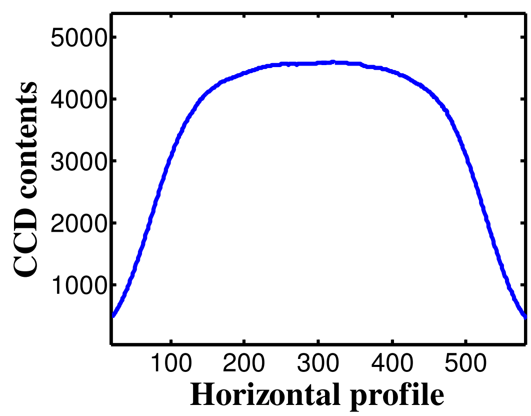

Figure 4: 3 mm degrader: 13.6 MeV

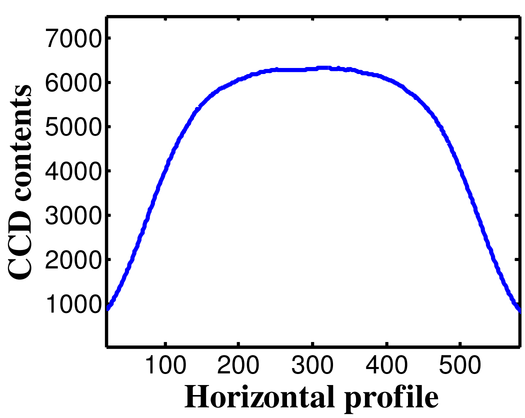

Figure 5: 3.5 mm degrader: 9.5 MeV

Details of the low energy DDD campaign

								IF QSX1=4		QSX1 setting corrected							
ESA	Energy	Degrader	**Fluence #p/cm2**	**flux #p/cm2/s**	duration s	duration min	Calibration #protons/cm^2/MU	Beam current nA	MMU	**QSX1 setting**	**MMU set MMU**	**BIM rate Hz**	QSX1 cor factor	**Act.time**	**Mean.flux**	Act.fluence	MMU left
optoi1	**25**	**1**	**4,00E+09**	**5,00E+07**	8,00E+01	1,33	504,65	4,95E+00	7,926	**4**	**7,926**	**9,918E+04**	1	**90,073**	**4,44E+07**	4,00E+09	0,0000
optoi2	**25**	**1**	**2,00E+10**	**1,00E+08**	2,00E+02	3,33	504,65	9,91E+00	39,632	**4**	**39,632**	**1,983E+05**	1	**410,387**	**4,87E+07**	2,00E+10	0,0000
optoi3	**25**	**1**	**7,00E+10**	**1,00E+08**	7,00E+02	11,67	504,65	9,91E+00	138,711	**4**	**138,711**	**1,983E+05**	1	**700,129**	**1,00E+08**	7,00E+10	0,0000
optoi4	**25**	**1**	**2,00E+11**	**5,00E+08**	4,00E+02	6,67	504,65	4,95E+01	396,317	**3**	**39,632**	**9,918E+04**	0,1	**407,129**	**4,91E+08**	2,00E+11	0,0000
optoi5	**25**	**1**	**5,00E+11**	**5,00E+08**	1,00E+03	16,67	504,65	4,95E+01	990,792	**3**	**99,079**	**9,918E+04**	0,1	**983,184**	**5,09E+08**	5,00E+11	0,0000

Annex 2 – details of the TID campaign

ESTEC ^{60}Co Facility

Keplerlaan, 1 2200AG Noordwijk Zh (NL)

RADIATION TEST SUMMARY

Number : **TEC-QEC/RP 20229 Version 1.0** *Date :* **18 Apr 2013**

Test Requester : Name	**Optol**
Address	Via Vienna n°8, 38121 Gardolo (TN) - Italia
Personnel present :	M.Bregoli
Project/Cost Code :	ECI2
Devices/Components irradiated :	Optocouplers
Device/Component details : *(conditions and identification)*	OIER10 (Optol), 4N49 (Micropac)

Dosimetry Chain used :	- A -
Dosimeter :	Farmer model 2680 – s/n 390
Gas Ionisation Chamber :	NE Type 2571 – s/n 2915
Measured Dosimetry :	Total Ionising Dose in [Gy] (water)
Dosimetry Procedure :	ESCC 22900 section 4.1.1 TEC-QEC/PR001 ***(Total Ionising Dose accredited by RvA according to ISO/IEC 17025.2005 Certificate No. L517)***

(With the exception of the above specified dosimetry equipment, ESTEC ^{60}Co Facility does not assume any liability for the calibration status of any other equipment lent to the requester)

ESTEC ^{60}Co Facility

Keplerlaan, 1 2200AG Noordwijk Zh (NL)

Irradiation Test Campaign Details

Source Activity : 69.32 TBq *on date :* 13 March 2013

	units	*Min.*	*Max.*	Time-weighted Average
Temperature	°C	*20.4*	*20.8*	*20.53*
Pressure	mbar	*988.3*	*1023.9*	*1010.18*
Relative Humidity	%	*23.9*	*39.8*	*31.84*

Dosimeter position relative to ^{60}Co source		
X	cm	16
Y	cm	211
Z	cm	0

Run	***Start Date & Time (CET)***	***End Date & Time (CET)***	***Total Ionising Dose [Gy] (water)***	***Dose Rate [mGy/h] (water)***
1	13/03/2013 17:35	14/03/2013 08:54	62.95 Gy	4.109 Gy/h
2	14/03/2013 09:20	14/03/2013 16:55	31.09 Gy	4.106 Gy/h
3	14/03/2013 17:11	15/03/2013 15:56	93.43 Gy	4.105 Gy/h
4	15/03/2013 16:20	18/03/2013 13:58	285.4 Gy	4.098 Gy/h
5	18/03/2013 14:23	19/03/2013 16:24	105.3 Gy	4.046 Gy/h
6	19/03/2013 18:27	21/03/2013 15:33	182.5 Gy	4.047 Gy/h
7	21/03/2013 15:40	25/03/2013 10:16	365.4 Gy	4.033 Gy/h
8	25/03/2013 11:33	26/03/2013 16:18	116.0 Gy	4.033 Gy/h
9	26/03/2013 16:48	27/03/2013 11:26	75.12 Gy	4.034 Gy/h
10	27/03/2013 11:58	02/04/2013 09:08	566.8 Gy	4.044 Gy/h
		Total	1.884 kGy	

Note: *The uncertainty budgets (according to TEC-QEC/PR001 section 12) are: 4.2 % (k=2) for absorbed dose to water and 4.4% (k=2) for absorbed dose rate to water*

Notes:

Alessandra Costantino
(TEC-QEC Radiation Test Engineer)

Christian Poivey
(TEC-QEC Acting Section Head)

PLEASE REMEMBER TO COMPLETE THE CUSTOMER SATISFACTION SURVEY AT :
http://task.esa.int/sites/WG/CO60Q/Lists/Customer%20Satisfaction/overview.aspx
AND SEND A COPY OF THE FINAL REPORT

RADIATION TEST SUMMARY

Number : **TEC-QEC/RP 20228 Version 1.0** *Date :* **18 June 2013**

Test Requester : Name	**Optol**
Address	Via Vienna n°8, 38121 Gardolo (TN) - Italia
Personnel present :	M.Bregoli
Project/Cost Code :	ECI2
Devices/Components irradiated :	Optocouplers
Device/Component details	OIER10 (Optol), 4N49 (Micropac)
(conditions and identification) :	See radiation test plan : P10.004.60

Dosimetry Chain used :	- C -
Dosimeter :	Farmer model 2680 – s/n 491
Gas Ionisation Chamber :	NE Type 2571 – s/n 3573
Measured Dosimetry :	Total Ionising Dose in [Gy] (water)
Dosimetry Procedure :	ESCC 22900 section 4.1.1 TEC-QEC/PR001 ***(Total Ionising Dose accredited by RvA according to ISO/IEC 17025.2005 Certificate No. L517)***

(With the exception of the above specified dosimetry equipment, ESTEC ^{60}Co Facility does not assume any liability for the calibration status of any other equipment lent to the requester)

Irradiation Test Campaign Details

Source Activity : 69.32 TBq *on date :* 13 March 2013

	units	*Min.*	*Max.*	Time-weighted Average
Temperature	°C	*20.40*	*21.90*	21.14
Pressure	mbar	*988.3*	*1033*	1012
Relative Humidity	%	*23.90*	*50.10*	37.87

Dosimeter position relative to ^{60}Co source		
X	cm	67
Y	cm	679
Z	cm	32

Run	***Start Date & Time (CET)***	***End Date & Time (CET)***	***Total Ionising Dose [Gy] (water)***	***Dose Rate [mGy/h] (water)***
1	13-03-13 17:35	14-03-13 8:54	6.534 Gy	426.500 mGy/h
1	13-03-13 17:35	14-03-13 8:54	6.534 Gy	426.500 mGy/h
2	14-03-13 8:57	14-03-13 9:17	141.1 mGy	425.800 mGy/h
3	14-03-13 9:20	14-03-13 16:55	3.226 Gy	426.000 mGy/h
4	14-03-13 17:11	15-03-13 15:56	9.694 Gy	425.900 mGy/h
5	15-03-13 16:20	18-03-13 13:58	29.62 Gy	425.400 mGy/h

6	18-03-13 14:23	19-03-13 16:24	11.01 Gy	423.200 mGy/h
7	19-03-13 18:27	21-03-13 15:33	19.07 Gy	422.800 mGy/h
8	21-03-13 15:40	25-03-13 10:16	38.24 Gy	422.100 mGy/h
9	25-03-13 11:33	26-03-13 16:18	12.12 Gy	421.500 mGy/h
10	26-03-13 16:48	27-03-13 11:26	7.846 Gy	421.300 mGy/h
11	27-03-13 11:58	02-04-13 9:08	59.09 Gy	421.600 mGy/h
12	02-04-13 9:15	05-04-13 14:30	32.52 Gy	421.000 mGy/h
13	05-04-13 14:51	05-04-13 15:38	329.3 mGy	417.500 mGy/h
14	05-04-13 15:41	08-04-13 16:21	30.18 Gy	415.400 mGy/h
15	08-04-13 16:52	09-04-13 15:36	9.448 Gy	415.600 mGy/h
16	09-04-13 15:45	09-04-13 15:48	26.14 mGy	409.100 mGy/h
17	09-04-13 15:52	09-04-13 15:54	13.59 mGy	404.200 mGy/h
18	09-04-13 15:57	09-04-13 16:00	20.98 mGy	410.400 mGy/h
19	09-04-13 16:06	15-04-13 9:02	57.12 Gy	417.100 mGy/h
20	15-04-13 9:28	16-04-13 11:29	10.85 Gy	417.200 mGy/h
21	16-04-13 14:33	17-04-13 9:30	7.972 Gy	420.900 mGy/h
22	17-04-13 9:43	17-04-13 12:06	1.003 Gy	420.100 mGy/h
23	17-04-13 12:20	17-04-13 13:38	550.3 mGy	419.700 mGy/h
24	17-04-13 13:46	17-04-13 18:35	2.024 Gy	420.100 mGy/h
25	17-04-13 18:39	17-04-13 19:49	484.3 mGy	419.500 mGy/h
26	17-04-13 19:53	18-04-13 12:52	7.135 Gy	419.900 mGy/h
27	18-04-13 14:19	19-04-13 14:20	10.08 Gy	420.000 mGy/h
28	19-04-13 15:57	22-04-13 15:57	30.20 Gy	419.400 mGy/h
29	22-04-13 17:07	25-04-13 17:26	30.33 Gy	419.300 mGy/h
30	25-04-13 18:35	29-04-13 9:49	36.53 Gy	418.800 mGy/h
31	29-04-13 11:11	29-04-13 13:25	940.4 mGy	419.600 mGy/h
32	29-04-13 13:35	29-04-13 18:03	1.879 Gy	420.200 mGy/h
33	29-04-13 18:06	01-05-13 9:57	16.74 Gy	420.100 mGy/h
34	01-05-13 10:02	01-05-13 14:31	1.884 Gy	420.200 mGy/h
35	01-05-13 14:34	01-05-13 17:07	1.070 Gy	420.000 mGy/h
36	01-05-13 17:12	02-05-13 9:30	6.853 Gy	420.200 mGy/h
37	02-05-13 9:38	02-05-13 17:06	3.131 Gy	419.500 mGy/h
38	02-05-13 17:09	03-05-13 9:19	6.799 Gy	420.600 mGy/h
39	03-05-13 9:22	03-05-13 12:05	1.140 Gy	420.000 mGy/h
40	03-05-13 12:20	03-05-13 18:30	2.592 Gy	420.700 mGy/h
41	03-05-13 18:32	06-05-13 9:06	26.30 Gy	420.300 mGy/h
42	06-05-13 9:16	06-05-13 16:01	2.835 Gy	420.100 mGy/h
43	06-05-13 17:41	07-05-13 9:17	6.554 Gy	420.000 mGy/h

44	07-05-13 9:20	07-05-13 10:45	595.8 mGy	419.000 mGy/h
45	07-05-13 10:50	07-05-13 17:25	2.760 Gy	419.600 mGy/h
46	07-05-13 17:33	08-05-13 9:15	6.591 Gy	419.600 mGy/h
47	08-05-13 9:19	08-05-13 10:24	453.1 mGy	418.900 mGy/h
48	08-05-13 10:28	08-05-13 17:37	3.000 Gy	419.300 mGy/h
49	08-05-13 17:40	10-05-13 9:37	16.75 Gy	419.000 mGy/h
50	10-05-13 9:44	10-05-13 16:03	2.650 Gy	419.200 mGy/h
51	10-05-13 16:12	13-05-13 9:40	27.36 Gy	417.900 mGy/h
52	13-05-13 11:15	15-05-13 10:27	19.76 Gy	418.600 mGy/h
53	15-05-13 10:40	16-05-13 16:37	12.53 Gy	418.200 mGy/h
54	16-05-13 19:52	17-05-13 14:38	7.845 Gy	418.300 mGy/h
55	17-05-13 14:51	21-05-13 9:42	37.90 Gy	417.200 mGy/h
56	21-05-13 10:40	21-05-13 13:33	1.146 Gy	397.000 mGy/h
57	21-05-13 13:49	24-05-13 10:33	27.19 Gy	395.700 mGy/h
58	24-05-13 11:43	27-05-13 9:31	29.04 Gy	416.100 mGy/h
59	27-05-13 10:10	28-05-13 11:42	10.60 Gy	415.200 mGy/h
60	28-05-13 12:01	28-05-13 14:42	1.109 Gy	414.800 mGy/h
61	28-05-13 14:47	29-05-13 16:28	10.66 Gy	415.200 mGy/h
62	29-05-13 16:51	30-05-13 16:25	9.777 Gy	414.800 mGy/h
63	30-05-13 16:33	03-06-13 14:44	39.07 Gy	414.800 mGy/h
64	03-06-13 15:26	04-06-13 13:12	7.098 Gy	326.200 mGy/h
65	04-06-13 13:35	05-06-13 9:23	8.199 Gy	414.000 mGy/h
66	05-06-13 9:31	11-06-13 13:13	62.38 Gy	422.400 mGy/h
		Total	886.6 Gy	

Note: *The uncertainty budgets (according to TEC-QEC/PR001 section 12) are: 4.2 % (k=2) for absorbed dose to water and 4.4% (k=2) for absorbed dose rate to water*

Notes:

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