Compendium of Current Proton-Induced Radiation Effect Results on Power Regulators

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***Abstract*—This paper presents the latest test results of power regulator devices under proton irradiation. Single event effects (SEE) and accumulated total ionizing dose (TID) effects are investigated, analyzed and discussed.**

***Index Terms*—Total ionizing dose, Single event effects, power devices, space irradiation, spacecraft electronics**

I. Introduction

The German Aerospace Center (DLR) has characterized several power regulator devices under proton irradiation for the use in their development of spacecraft avionics. The primary focus is the investigation of single event effects (SEE) responses to verify if potential power devices are applicable for a low-cost but also reliable space mission of the DLR. The tested power regulators are buck converters, low-dropout (LDO) regulators and integrated, multi-channel power devices. The characterization has been performed within two test campaigns (2018 and 2019), using the same accelerator facility.

Experimental details and test descriptions are presented in section II. Results and their discussion are given in section III. Section IV concludes the content of this paper.

II. Experimental details

A. Test Conditions

All DUTs were irradiated at ambient temperature (21-25 °C) using the proton irradiation facility of the Kernfysisch Versneller Instituut (KVI). The DUTs were investigated under proton energies of 50, 70, 100, 120, 150 and 185 MeV and only a single test campaign has been performed with each setup , thus no evidence was collected on the variations of test conditions over time. Changes in the setup between runs will be described. A minimum target fluence of 1E+10 particles/cm² was selected and the flux was individually chosen according to the SEE response of the DUT. Two to three samples per DUT have been selected, depending on the time constraint, complexity of the DUT and the corresponding setup. Relevant voltages and currents were continuously monitored to observe abnormalities with respect to SEEs and TID-related degradation effects. Destructive damages due to single event latchup (SEL) were prevented by individual current sensing on each device and a current limitation of the power supply. In case of an SEL, which threshold is usually defined with an additional current offset of 25% and a time-period of 1 second, the power supply is triggered to perform a hard shutdown of the corresponding output and a re-enabling after 1 second. During switch-off time, the beam was disabled. Output states, such as power-good signals and voltages were captured using a data acquisition (DAQ) module with a sample rate of 10 kHz. Longer single event transients (SET) can be observed with that setup but are not highly expected. Short transients might be recognized but the waveform will be under-sampled. Degradation due to TID effects can be observed and are more likely expected. Short SETs were only investigated in the second test campaign in 2019 using a high-speed oscilloscope.

The tested power regulators were operated, if not otherwise defined, with a fixed load configuration. Detailed operation configurations are presented the DUT description section.

B. Devices Under Test

Six different regulators were tested for their behavior under proton irradiation. For the description of the test setup and sampled signals the names of the associated pins on the chips were used to unambiguously describe the hardware.

1) LT8613

No Process or lot information

The LT8613 [1] is a constant-current, constant-voltage step-down converter with up to 6 A output current and a rated maximum input voltage of 42 V. All samples were supplied with 34 V. Three of those were configured for a fixed 5 V output voltage with a 2 Ω load. Another three samples were configured for 2 A constant-current output and connected to a 5 Ω load resulting in about 10 V on the output. Six 22µF ceramic capacitors were connected to the output for a total of 132µF output capacitance.

The output voltages as well as the current monitor and power good (PG) signals from the chip were sampled for all devices.

2) LT3007

No Process or lot information

The LT3007 [2] is an LDO rated up to 45 V and 20 mA output current. Three samples were examined at 34 V input voltage and loaded with a 33 Ω resistor. To maximize the voltage drop, the output was directly connected to the feedback pin, resulting in 0.6 V output voltage and 18 mA output current. 4.4 µF of output capacity were realized with two ceramic capacitors in parallel. The output voltage was sampled with the DAQ.

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TABLE I
SUMMARY OF SEE AND TID RESULTS FOR ALL TESTED DUTS

DUT	Manufacturer	Fluence [particles/cm²]						SEE	TID [krad]	Samples	Remark
		184 MeV	150 MeV	120 MeV	100 MeV	70 MeV	50 MeV				
LT8613CC	Linear Technology	5.94E+09	-	-	-	-	-	No SEL SET: >184MeV No SEFI	0.36	3	Device broken
LT8613CV	Linear Technology	2.19E+10	-	-	-	-	-	No SEL SET: >184MeV No SEFI	1.33	3	Device broken
TPS62745	Texas Instruments	1.00E+11	-	1.00E+11	-	4.19E+10	-	No SEL SET: >70MeV No SEFI	18.62	2	Device broken
LT3007	Linear Technology	1.00E+11	-	5.00E+10	-	5.99E+10	-	No SEL SET: >70MeV No SEFI	17.89	3	Device broken
ADP5052	Analog Devices	1.00E+11	1.00E+11	-	1.00E+11	1.00E+11	1.00E+11	No SEL SET: >=50MeV No SEFI	52.02	2	Device broken
TPS5450	Texas Instruments	1.00E+10	1.00E+10	-	1.00E+10	1.00E+10	1.00E+10	No SEL SET: >50MeV No SEFI	5.20	3	
NCP3170	Onsemi	1.00E+10	1.00E+10	-	1.00E+10	1.00E+10	1.00E+10	No SEL. SET: >100MeV No SEFI	5.20	3	

3) TPS62745

No Process or lot information

The TPS62745 [3] is an ultra-low power step-down converter for battery applications up to 10 V. The devices were configured for 3.3 V output and loaded with a 20 Ω resistor. Two 10 µF ceramic capacitors are connected in parallel on the output. The output voltage and the digital PG signal were sampled during the test. Two samples were tested due to a wiring error.

4) ADP5052

0.35µm DMOS – No lot ID

The ADP5052 [4] is a four channel buck regulator with an additional LDO rated for 15 V. Buck regulator channel one and two are rated for 4 A, channel three and four are rated for 1.2 A and the LDO channel is rated for 200 mA. For the test, two identically configured samples based on evaluation boards were used. A 6 V input voltage was used during this test. The LDO was configured for 2.5 V @ 140mA and the step-down channels one to four were configured for 1.2 V @ 3 A, 3.3 V @ 1 A , 1.8 V @ 0.75 A and 5 V @ 0.8 A. The setup was chosen related to the intended application.

The capacities on the outputs were: CH1: 188 µF, CH2: 188 µF, CH3: 44µF, CH4: 44 µF, LDO: 1 µF

5) TPS5450

No Process or lot information

The TPS5450 [5] buck regulator is rated for 36 V and 5 A output current. Three samples supplied by 16.8 V were tested with an output voltage of 3.5 V and a load of 1.1 Ω. Three 100 µF tantal capacitors were connected to the ouput for 300 µF of total output capacity. During the test we monitored the input and output voltage as well as the input current.

6) NCP3170

No Process or lot information

The NCP3170 [6] integrated synchronous buck converter rated for 18 V and 3 A. Three samples of the device were supplied with a 5 V input voltage and configured to output 1.5 V. This represented the largest input to output voltage difference in the intended application. A total of 44 µF was connected to the outputs for stability. They were loaded with an output current of 1.5 A. The output voltage and the PG signal were monitored during the test.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Test Results Overview

All devices showed a response to proton irradiation and most of the devices ceased to work due to radiation induced effects. Due to the linear energy transfer (LET) of low energy protons, TID and SEE are equally possible. Table I shows the summary of all devices being tested with the corresponding fluences to all tested energies as well as the SEE results and the accumulated TID. The effects on specific devices are further discussed in the following paragraph.

B. Test Results Discussion

During the first test campaign in 2018 we started the tests with low proton energies and moved up to higher energies to better understand the susceptibility of the devices for SEE and to avoid early destructive events. However, we did not encounter any SELs. For the second campaign (2019) we started with the higher energies to reduce the influence of TID effects early in the test. The first three devices were tested in the 2019 campaign, starting with the higher energies.

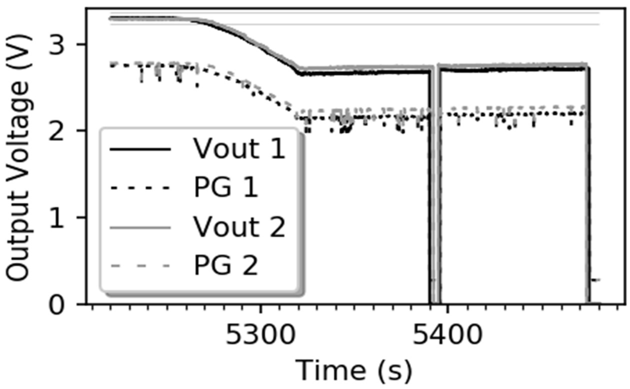

Fig. 2. Output voltage drift of the two TPS62745 samples during proton irradiation. The 70 MeV beam was stopped at 5320 s. Light grey lines indicate specification limits.

1) LT8613

The test was conducted at 184 MeV proton energy with a flux of 1E+7 $\text{protons/cm}^2 \cdot s$ and the output voltage of all three devices went to zero after about 600 s within a 20 s timeframe. The sampled output voltages do not show any transients, however minor variations were captured with the oscilloscope. The input current of the devices went down to near zero and did not increase during the test.

In the constant voltage configuration the devices operated to a higher fluence, but they failed similar to the constant current configuration with zero output voltage. Cycling the input voltage did not restore the output voltage.

2) LT3007

Transients on the output voltage of the LT3007 were observed on the oscilloscope; these were of a few 100 µs and are not recorded by the DAQ. All of the transients were in the direction of lower voltages. During the 70 MeV and 120 MeV test runs we saw a change in the output voltages of all three devices as shown in Fig. 1. The drift is faster during the 70 MeV test (beginning at 1900 s in Fig. 1). All devices failed to zero output voltage within 10 s of each other. Between tests (and during some beam stops) there were periods without irradiation during which the output voltage decreased slightly.

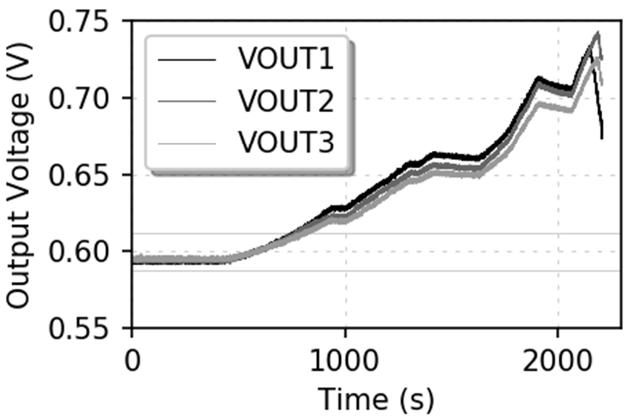

Fig. 1. Output voltage drift of the LT3007 samples during proton irradiation. 184 MeV beam up until 1390 s, 120 MeV beam from 1600 s to 1915 s, 70 MeV beam from 2050 s till the end. Light grey lines indicate specification limits.

In general, this behavior hints to a TID related degradation with some potential for annealing which should be further investigated.

3) TPS62745

The TPS62745 showed around 10 minor SETs on the output voltage per sample during the 120 MeV and 184 MeV tests, all transients were towards lower voltages. The PG signal did not show any transients. During the 70 MeV, test the output voltage degraded on both samples as can be seen in Fig. 2. the irradiation stops at 5320 s and no further degradation is observed. A power cycle at 5390 s did not restore the proper output voltage. However, both converters still turned on. The simultaneous degradation of both devices could be a TID related effect, which needs further investigation.

4) ADP5052

The ADP5052 and all following devices were tested during the 2018 campaign where we started with the lower proton energy of 50 MeV and moved up to 184 MeV.

Minor SETs were found during all test runs. During the 100 MeV test output 3 broke down on both DUTs. In Fig. 3, the output voltage of output 3 on DUT 1 begins to fall to zero erratically and then starts to oscillate between on and off status with a rising frequency. The same behavior was observed on other outputs during later runs. Remarkably, the power-good signal did not indicate a broken output. A power cycle did not resolve the issue. The behavior could potentially be related to a destructive event in the control logic of the specific converter channel.

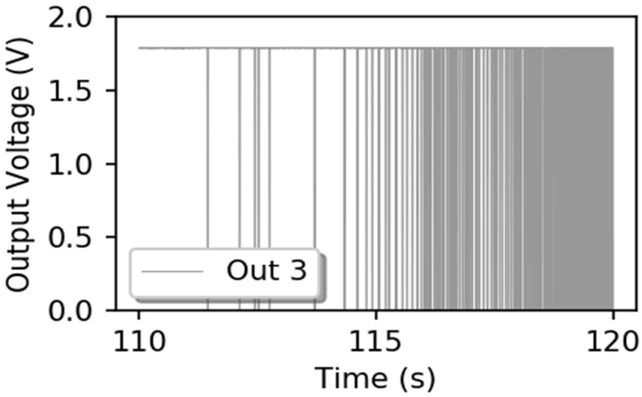

Fig. 3. Oscillation of Output 3 on the ADP5052

5) TPS5450

The TPS5450 did not show any TID related degradation after all test runs with an accumulated TID of 5.2 krad (SiO_2). However, all samples showed transients under irradiation with protons of more than 70 MeV. We counted a total of 8 SETs for all samples during the tests. Fig. 4 shows transients from the 100 MeV test run compared to the startup behavior of the converter.

The curves show a very similar rise time, so the transients could be potentially explained by a glitch in the softstart logic as shown for the LT8610 in [6]. However, further study is needed to confirm this. Due to the lack of a softstart pin no direct measurement is possible.

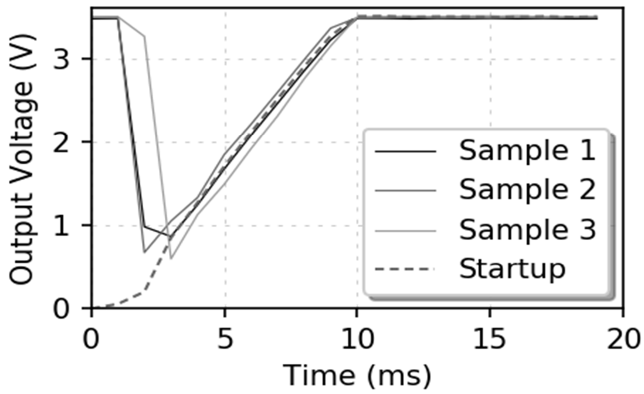

Fig. 4. Output transients of the three TPS5450 samples during 100 MeV proton irradiation compared to the startup behavior.

6) NCP3170

During the irradiation with a beam energy of 100 MeV we observed one SET on the output voltage for each of the three samples independently at different times. In each case, the output voltage dropped below 0.4 V for a short period and recovered to the correct level. In each of these cases the power good signal correctly indicated a fault. In one instance we also observed a transient on the PG signal without any effect on the respective output voltage.

All transients are about 5 ms long and towards a lower output voltage. In Fig. 5 two SET are shown aligned with the startup slope, revealing their identical shape. This hints to a ST-related behavior as described for the TPS5450.

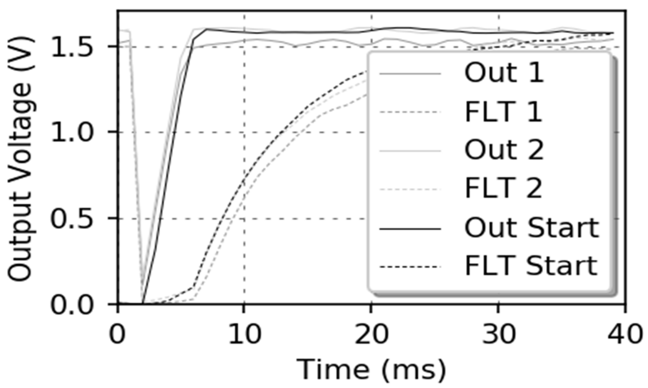

Fig. 5. Output transients of the three NCP3170 samples during proton irradiation compared to startup behavior

IV. CONCLUSION

Recent proton-induced damages and accumulated TID effects on a variety of commercial power regulators have been presented. No major variations in the SEE and TID response between the tested samples of each device have been observed. Anyhow, the here presented data needs to be used with caution since no lot specific testing nor qualification has been performed. The observed degradation effects, considered to be caused by the accumulated dose need to be verified on a separated test campaign such as under gamma ray irradiation on a Cobalt-60 source. Especially for the TPS5450 and NCP3170 a TID test campaign is of interest, as the devices performed well under proton irradiation.

For the LT3007 a test at lower dose rates is planned to further investigate the practical impact of the output voltage drift. It is also planned to anneal the samples from the proton test at higher temperatures to investigate the possibility of restoring the original output voltage.

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