# LT7101 SEE TEST REPORT

## 105V, 1A Low EMI Synchronous Step-Down Regulator with Fast Current Programming PassThru

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# CHANGE LOG

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# 2. INTRODUCTION

The aim of this Single Event Effect test campaign was to evaluate the SEE radiation hardness level of the LT7101 buck converter component from Linear Technologies, especially regarding destructive single event effects,Signle Event Functional Interrupts (SEFI), and Single Event Transients (SET), as well as their dependence on bias voltage and load. Tests were performed at room temperature and at LET of 46 MeV · cm²/mg and 62 MeV · cm²/mg.
The component is selected from an ESA internal list of Commercial Of-The-Shelf (COTS) components, which contains components of high importance for ESA projects. The reported data can be used to derive information of a Safe-Operating-Area (SOA) for this device.

The test was carried out on 20-21 March and on the 8-9 June 2023 at UCLouvain in Belgium.

# 3. ACRONYMS

| | |
|---|---|
| HIF | Heavy Ion Facility |
| COTS | Commercial-Off-The-Shelf |
| DSEE | Destructive Single Event Effect |
| DUT | Devices Under Test |
| HIF | Heavy Ion Facility |
| LDMOS | Lateral-Diffused Metal-Oxide Semiconductor |
| LET | Linear Energy Transfer |
| MIP | Microwaved Induced Plasma |
| MOSFET | Metal-Oxide-Semiconductor-Field-Effect Transistor |
| NDSEE | Non-Destructive Single Event Effect |
| PC | Power Cycle |
| SEB | Single Event Burnout |
| SEE | Single Event Effect |
| SEFI | Single Event Functional Interrupt |
| SEGR | Single Event Gate Rupture |
| SEL | Single Event Latchup |

| | |
|---|---|
| SET | Single Event Transient |
| SOA | Safe Operating Area |

# 4. HEAVY ION IRRADIATION FACILITY

The heavy ion facility used for this test campaign is the HIF of UC-Louvain in Belgium. The facility offers a cocktail of 9 ions including Xe-ions and Rh-ions which are used during this campaign. In the following table the available particles inside the cocktail are displayed.

*Table 1: Available Ions at UCL (from [1])*

| M/Q | Ion | Energy [MeV] | Range [µm] | LET [MeV/(mg/cm²)] |
|---|---|---|---|---|
| 3,25 | $^{13}C^{4+}$ | 131 | 269.3 | 1,3 |
| 3,14 | $^{22}Ne^{7+}$ | 238 | 202,0 | 3,3 |
| 3,37 | $^{27}Al^{8+}$ | 250 | 131,2 | 5,7 |
| 3,27 | $^{36}Ar^{11+}$ | 353 | 114,0 | 9,9 |
| 3,31 | $^{53}Cr^{16+}$ | 505 | 105,5 | 16,1 |
| 3,22 | $^{58}Ni^{18+}$ | 582 | 100,5 | 20,4 |
| 3,35 | $^{84}Kr^{25+}$ | 769 | 94,2 | 32,4 |
| 3,32 | $^{103}Rh^{31+}$ | 957 | 87,3 | 46,1 |
| 3,54 | $^{124}Xe^{35+}$ | 995 | 73,1 | 62,5 |

# 5. DEVICES UNDER TEST

In Table 2 the parameters of the Device under Test (DUT) are given.

*Table 2: Description of the DUT*

| Manufacturer | Product | Uin,max (V) | Uout,max (V) | Uout,min (V) | Id,cont,max (A) | frequency (MHz) |
|---|---|---|---|---|---|---|
| Analog Devices | LT7101 | 105 | 105 | 1 | 1 | 0.2-2 |

This device is a synchronous buck converter with a half bridge configuration which is used to step down a voltage with a switching application. For the device a specific application close to the usual application as presented in the datasheet, was developed. In Figure 1, a usual application for this synchronous buck converter with the internal MOSFETs (LDMOS) is given.

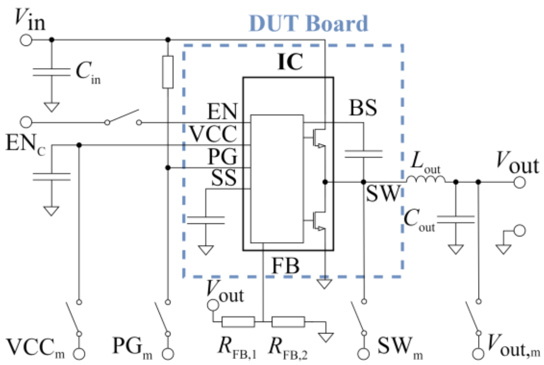


*Figure 1: Typical application synchronous buck converter*

In Figure 2 the Block diagram of the device is shown and in Figure 3 the decapsulated die can be seen.

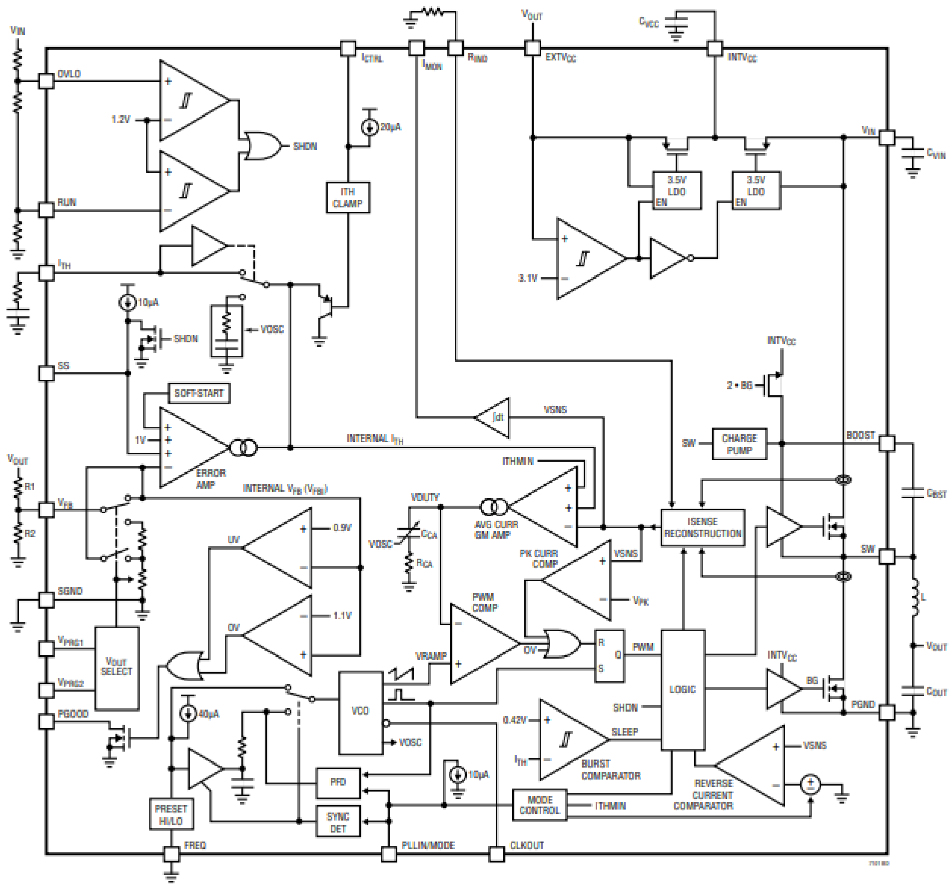


*Figure 2: Block Diagram of the LT7101*


*Figure 3:Microscope Picture of the package marking of the LT7101*

# 6. TEST PREPARATION

## 6.1. Sample preparation

Due to the limited penetration depth of Xe-ions (75 µm in silicon), it is necessary to decapsulate the component to directly irradiate the die of the device. For the decapsulation procedure ESA internal equipment was used, including a laser to thin down the plastic capsulation and the use of a Microwave Induced Plasma (MIP) etcher, that etches down organic material and do not modify any inorganic material like silicon or metals. With these two tools a safe decapsulation was possible and in total 6 LT7101 devices have been decapsulated for the heavy ion test. After each procedure a full functionality test was performed to validate the nominal operation.

## 6.2. Test set-up

The test was performed with heavy ion irradiation at UCLouvain. The irradiation was performed in vacuum. The test was done in different application conditions. For the test, the following equipment, Table 3was used:

*Table 3: Test Equipment*

| Equipment | Name | Description |
|---|---|---|
| 2x Source meter | Keithley 2612A | Providing the bias voltage/current and the Relay supply current |
| 1 x Voltage source | Keysight N6705C | Used to test voltages above 35 V (if no DSEE happened at lower voltage) |
| 1x 4 channel oscilloscope | Keysight DSOS804A | To observe all the parameters mentioned in Table 4 |
| 1x Laptop | | To acquire data and to set the test setup |

In Figure 4 the basic test setup with the equipment and the test boards inside the vacuum chamber is visualized. Multiple different buck converters have been tested during the campaign. One of the test boards consist of the LT7101.

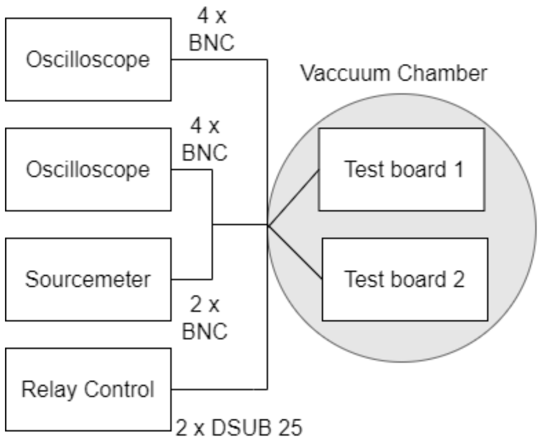


*Figure 4: Test setup*

For fast DUT sample exchange, a DUT board was designed and used for every different device type. This DUT board is mounted via pin headers on a second board, named “radiation-test-board” with the application circuitry and measurement and control connections to the outside. In the following a basic overview of the setup is given.

In Figure 5 the DUT board can be seen. This board is then mounted on the radiation-test-board in Figure 6. Specific values for the capacitances and inductances were calculated for each board to ensure a worst-case electrical stress while maintaining stability of the device. The biasing can flexibly be adjusted by jumpers and relays. The relays can be used to switch between the DUTs. In addition, the parameters of the device can be measured individually, and the device can be enabled and disabled. The relays are controlled outside the chamber with a specific designed relay-control-board.

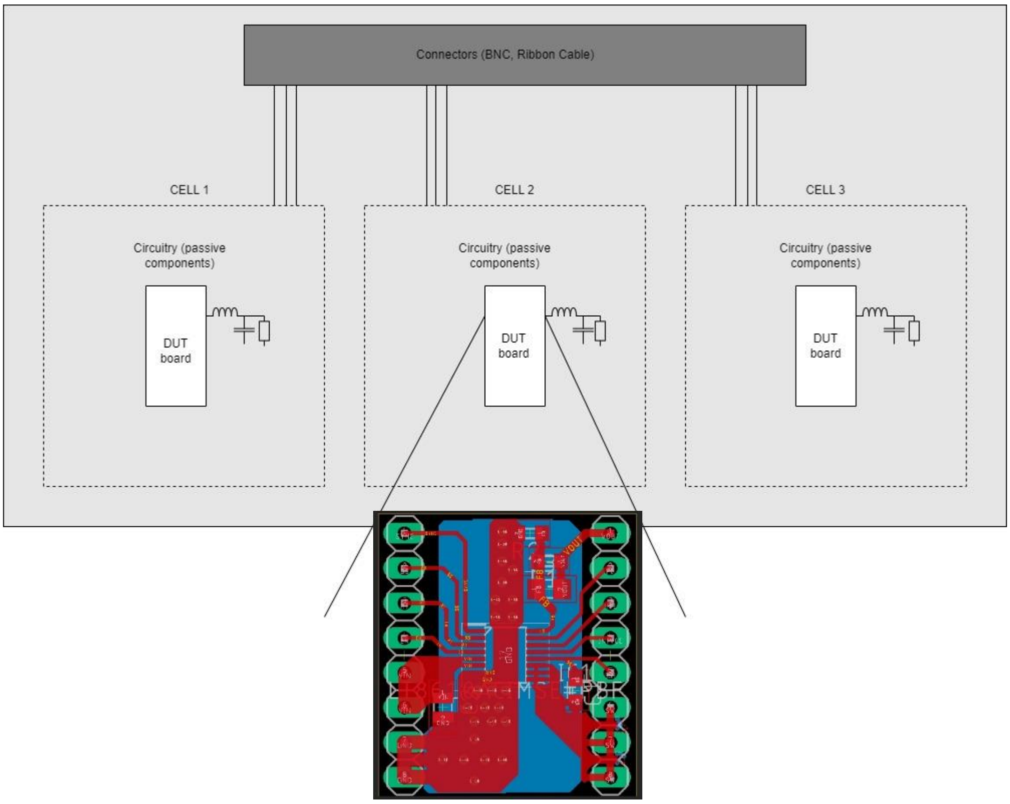


Figure 5: Visualization of the radiation-test-boards

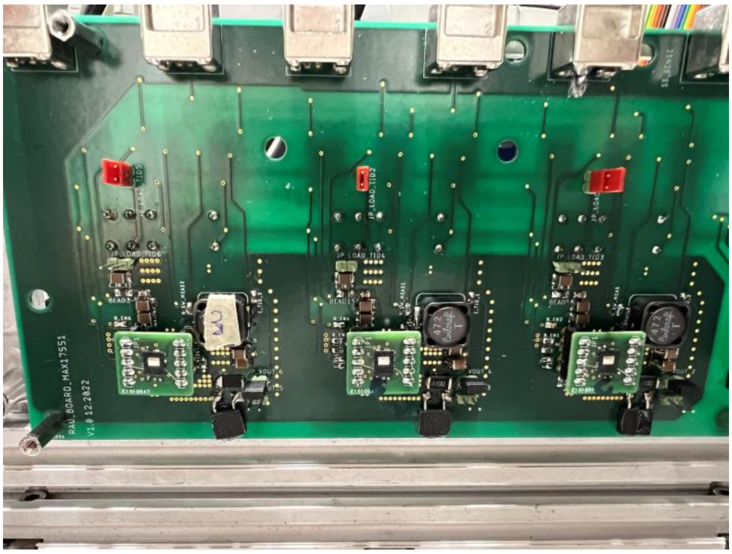

Figure 6: Top-side (left) and bottom-side (right) of the LT8610 test board

In Figure 7 an overview with the important capacitances is given. The value of the output capacitance is calculated to Cout = 80 µF, the input capacitance is Cin = 30 µF the output Inductance is Lout = 24 µH. . The input & output conditions are summarised together with the results in Table 8.

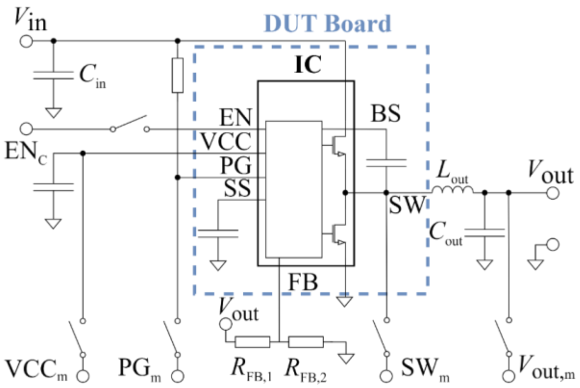


Figure 7: Simplified test setup with

*with varying input and output conditions described in Table 8.*

## 6.3. Measurement

As stated above, the use of relays allows an individual measurement for each DUT on the radiation-test-boards. All-important measurable device parameters are provided in Table 4.

*Table 4: Measurement Parameters*

| PIN/Parameter | Description | I/O | Measured | Type of Measurement |
|---|---|---|---|---|
| EN | Enable input pin | I | no | - |
| Vin | Supply input | I | yes | Input Voltage & Current |
| PVin | Power input | I | yes | Voltage & Current |
| SW | Switching node | O | yes | SW Voltage & (Frequency) |
| BST | Bootstrap pin | I | no | - |
| OCP_SEL | OCP select (here GND for 3 A) | I | no | - |

| | | | | |
|---|---|---|---|---|
| MODE | Auto selected (PWM, LLM) left open | I | no | - |
| SSCG | Spread Spectrum (deactivated) | I | no | - |
| RESET | Reset | I | yes | Voltage |
| Vout_dis | Discharges Vout | O | no | - |
| VOUT_SNS | Used for OVP, SCP | I | no | - |
| FB | Feedback pin | I | no | - |
| VREG | Output internal LDO | O | no | - |
| VCC | input internal LDO | I/O | no | - |
| Vout | Filtered output voltage | | yes | Voltage |

## 6.4. Acquisition of Data

The most important parameter of the DUT is the output voltage. Therefore, a trigger of the oscilloscope is set to the output voltage to observe whether the parameters are within the operating range. Also triggers on the PG have been set. As soon as the output voltage or PG voltage leaves the operating range, the oscilloscope acquires the data of SW pin, Vcc pin, Pgood pin and the output voltage. During the acquisition, the flux of the beam was adapted to not oversaturate the scope. That meaning, the saving time of the acquisition lead to the adjustment of the flux in such a way, that a safe acquisition of every SET was possible without the danger of losing the acquisition of other SETs. In addition, current measurements have been carried out to observe overcurrent situations, and, in the event of an overcurrent event, an internal designed delatching system was used to power off the device quickly to prevent a destruction in the event of a Single Event Latch up.

# 7. SINGLE EVENT EFFECTS RESULTS

## 7.1. Non-destructive Single Event Effects Results

In Table 5 an overview of the kind and number of the non-destructive SEEs is given. All changes in the output voltage are due to functional interrupts of the switching of the LT7101. NDSEE were solely captured during irradiation under Rhodium and not under Xenon.
There are different kinds of SEFIs measured and presented in Table 5. Each SEFI type was grouped based on the different behaviours of the device. No Power Cycle SEFI was measured during the irradiation. In Table 6 the number and kind of observed SETs is visualized. The number of events achieved was a trade-off between having enough statistical data & overall beamtime schedule. The observed SEFIs are dependent on the chosen Soft Start (SS) time. As can be seen in Figure 8, this takes the longest for the device to be operable again. A cross section and an upper bound cross section, calculated with the Upper-$N_{\text{events}}$ is presented in Table 5 and 6 and is calculated as follows [3]:

$$UpperN_{\text{events}} = 0.5 * CHISQ.INV.RT((1-CL)/2{,}2x(N_{\text{events}}+1)\ ,$$

With:

- $UpperN_{\text{events}}$, the upper limit of the confidence interval $N_{\text{events}}$ *of* observed.
- $CHISQ.INV.RT$, returns the inverse of the right-tailed probability of the chi-squared distribution.
- $CL$, Confidence Limits, here the 95% confidence limit shall be used.
- $N_{\text{events}}$, the number of observed events.

*Table 5: Description of the measured non-destructive SEFIs under Rh-ion irradiation and an Input voltage of 12 V and output current of 0.6 A*

| SEFIS with effect on Vout | Reference Figure | Cross section $cm^2$ | Upper-bound cross-section $cm^2$ | Fluence in $ions/cm^2$ | Maximum duration of SEFI in s | Number (#) of Events | Description |
|---|---|---|---|---|---|---|---|
| Auto SEFI | Fig. 8. | $1.22 \cdot 10^{-3}$ | $1.32 \cdot 10^{-3}$ | $5 \cdot 10^6$ | Up to $3 \cdot 10^{-2}$ | 612 | decrease to 0.5 V of nominal 5 Vout |
| Reset SEFI | - | $3.8 \cdot 10^{-6}$ | $5.8 \cdot 10^{-6}$ | $5 \cdot 10^6$ | Until reset | 19 | Shut down of the device, reset over enable pin necessary |
| Power Cycle SEFI | - | 0 | $3.69 \cdot 10^{-5}$ | $5 \cdot 10^6$ | Until PC | 0 | Shut down of the device, full power cycle necessary |
| Power Good SEFI | | 0 | $3.69 \cdot 10^{-5}$ | $5 \cdot 10^6$ | Until reset | 0 | Leads to a PG low signal with no effect on Vout or other parameters, reset via the enable pin necessary |

*Table 6: Description of the measured non-destructive SEEs under Rh-ion irradiation and an Input voltage of 12 V and output current of 0.6 A*

| SETs with effect on Vout | Reference Figure | Cross section $cm^2$ | Upper-bound cross-section $cm^2$ | Fluence in $ions/cm^2$ | Maximum duration of SEFI in s | Number (#) of Events | Description |
|---|---|---|---|---|---|---|---|
| Overvoltage SET | Fig. 7. | $4 \cdot 10^{-6}$ | $4.18 \cdot 10^{-6}$ | $5 \cdot 10^{6}$ | Up to $1 \cdot 10^{-4}$ | 12 | Increase of nominal 5 V out |
| Undervoltage SET | Fig. 8. | $52.4 \cdot 10^{-3}$ | $1.48 \cdot 10^{-3}$ | $5 \cdot 10^{6}$ | Up to $7 \cdot 10^{-4}$ | 262 | decrease to 4 V of nominal 5 Vout |

Different Kind of SETs can be observed on all devices. The undervoltage SET is a decrease of up to 2.9 V of the nominal 3.3 V. An example is visible in Figure 8.

Auto-SEFIs and reset- SEFIs can be observed on all DUTs. All SEFIs that lead to a shutdown are similar on the negative edges. This effect is due to a shutdown of the devices. As an example, typical SEFIs are shown in **Figure 8**. The figure shows an overlay of all SEFIs during a run. Once triggered, the auto-SEFI causes the device to shut down until a low voltage, about 2 V, is reached. The device then resumes back to normal operations automatically. The reset-SEFI can be observed as well and leads to a complete shutdown. After a reset or power cycle, the device restarts normally with the set soft start time, that was set via external capacitors. As soon as the output voltage leaves the nominal operating range, the PG pin triggers.

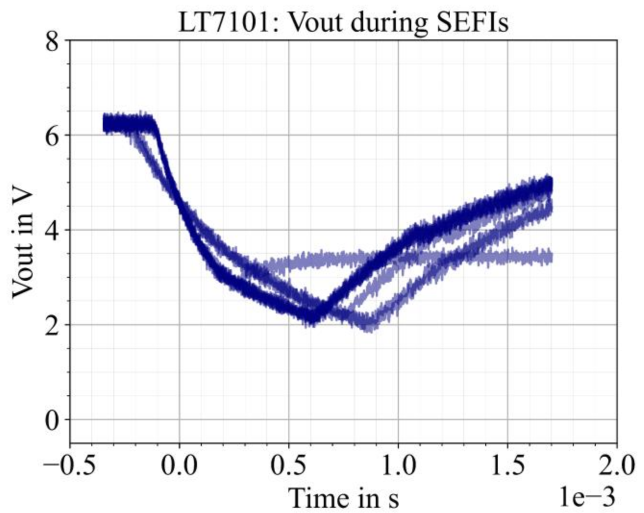


*Figure 8: Vout SEFI of the LT7101 after a overvoltage condition of 6 V instead the applied 5 Vout that led to the shutdown of the device*

## 7.2. DSEE Results

### 7.2.1. Latchups*

**A high inrush current was observed together with the overvoltage situations. However, since the exact functionality is not clear it might not be a Latch-up but another effect with a similar behaviour.*

The LT7101 experience latchups* during irradiation. With the used delatching system, a destructive event could be prevented. Without the delatching system the devices got destroyed. The Latch-ups led to high overcurrent spikes that potentially harm the device and the load. The number of SELs are indicated in the Safe Operating Area tables stated in the next chapter. In Figure 9 example of latchups are shown. A fast and constant high increase in the voltage and an inrush current in the device have been observed. The PG pin indicated low for a short time and went high again indicating wrongfully a correct functionality. There are different kind of overvoltage situations that went to different heights.

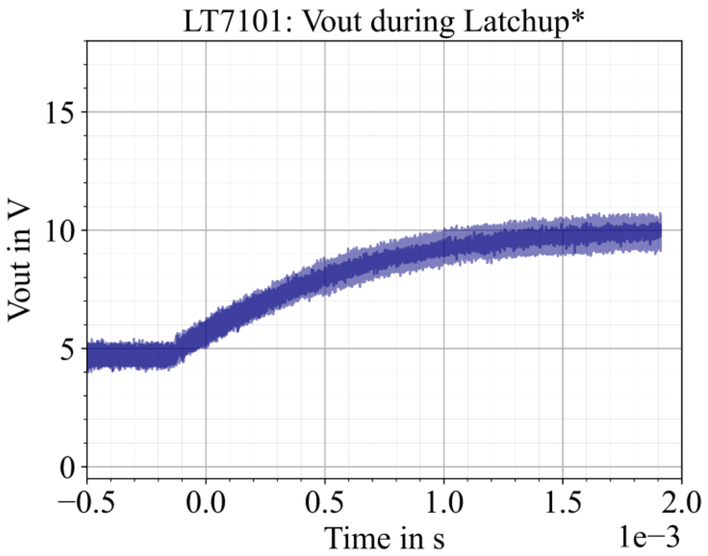


*Figure 9: output voltage during multiple latchups of the LT7101 at Vout of 5 V, Vin of 12 V and Iout of 0.6 A*

### 7.2.2. Destructive Events

The device was tested against DSEE during Rh-ion irradiation at a normal incidence angle of 0. In Table 7 a SOA is given. At an input voltage of 19 V and a low load the device survived the Rh-ion irradiation at an incident angle of 0. In Table 8 the SOA during Xe-Ion irradiation is given The reached fluence of all three devices was $10 \cdot 10^7$ ions/cm$^2$.

*Table 7: DSEEs and Safe Operating Area during Rh-ion irradiation with Vout 5 V*

| Vin (LET 46 MeV · cm²/mg) | Incident Angle @ 0° | | |
|---|---|---|---|
| | Low load (0.06 A) | High load (0.6 A) | Very High Load (1 A) |
| 10V | | | |
| 12V | | | |
| 15V | | | |
| 19V | | S3, S4 (5, 10 SEL) | S4 (10 SEL) |
| 24V | | | ~~S2~~ |
| 30V | | | ~~S1~~ |
| 40V | | | |

*Table 8: DSEEs and Safe Operating Area during Xe-ion irradiation*

| Vin (LET 60 MeV · cm²/mg) | Incident Angle @ 0° | | |
|---|---|---|---|
| | Low load (0.06 A) | High load (0.6 A) | Very High Load (1 A) |
| 10V | | | |
| 12V | | | |
| 15V | | | S5, S6 (10 SEL) |
| 19V | | | ~~S4~~ |
| 24V | | | |
| 30V | | | |
| 40V | | | |

In Figure 9 a visualization of the SOA is given.

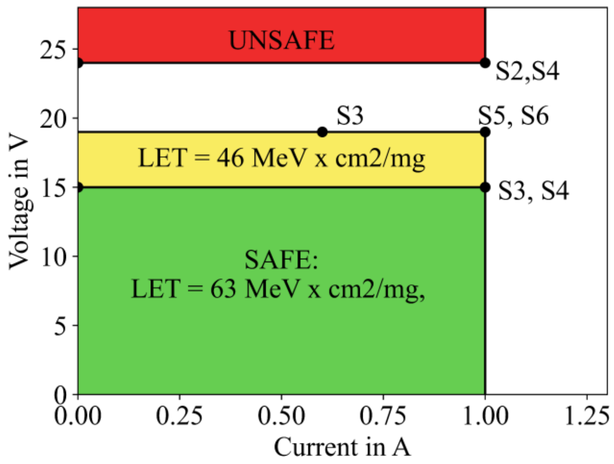


*Figure 10. Safe Operating Area of the LT8610 with the Unsafe are (red), safe for high-risk missions (yellow), and safe area (green)*

## 8. CONCLUSION

The aim of this test campaign is to evaluate the radiation hardness of the COTS LT7101 buck converter component tested at 2 LET and room temperature against NDSEE and DSEE. The component showed DSEE outside of the safe operating area. The SOA can be defined as follows:

- 15 V and 1 A for an LET of 62 $\mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{mg}$
- 19 V and 1 A for an LET of 46 $\mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{mg}$

The component showed not only DSEE but potentially SELs and a variety of non-destructive effects all of which need consideration in assessing the use of this part. The devices exhibit overvoltage situations that could potentially damage the load. In Table 10 a SEE summary is given.

The data provided in the report should be handled with caution considering traceability challenges in the use of COTS. However, the data gives an overview of different kinds of SEE and allows preparation for validation test campaigns and be able to identify possible mitigation techniques.

*Table 9: SEE Summary*

| Item | Description |
|---|---|
| Aim | SEE sensitivity evaluation of different synchronous buck converter devices for destructive SEE and SET |
| Biasing Conditions | 1. various input voltages and output currents<br>2. steady output voltage (5 V) and steady output switching frequency |
| Sample size | 3 devices to be tested for each final biasing condition for result confirmation |
| LET | $46\ \mathrm{MeV} \cdot \frac{\mathrm{cm}^2}{\mathrm{mg}}$, $60\ \mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{mg}$ |
| Fluence | 1. $10^7\ \mathrm{ions/cm}^{-2}$ for DSEE<br>2. various for SET and SEFI characterization |
| Environmental condition | Room temperature condition |
| Results | Safe Operating Area for DSEE<br>1. 1 A and 15 Vin @ $62\ \mathrm{MeV} \cdot \frac{\mathrm{cm}^2}{\mathrm{mg}}$<br>2. 1 A and 19 Vin @ $46\ \mathrm{MeV} \cdot \frac{\mathrm{cm}^2}{\mathrm{mg}}$.Soft-error & non-destructive SEL sensitivity (Rh irradiation):<br>1. Shutdown-SEFI, Reset-SEFI<br>2. Undervoltage SET, Overvoltage SET<br>3. SELs observed |

# 9. REFERENCES

[1] UCLouvain, Heavy Ion Facility, Heavy Ion Facility (HIF) | UCLouvain

[2] Analog Devices, LT7101 105 V, 1A, Low EMI Synchronous Step-Down Regulator with Fast Current Programming, LT7101 (Rev. 0) (analog.com)

[3] ESCC, Single Event Effect Test Method and Guidelines, ESCC Basic specification No. 25100

# 10. ANNEX

In the following tables the whole test campaign including different COTS devices is given.

| Run | Facility log # | Reminder Philipp file name | DUT | Vinput | Rout (Ohm) | Pitch (°) | Title (°) | Vacuum (Y/N)? | Beam collimation (Shape, size & position) | Particle | Energy (MeV) | LET Normal in Si (90°) [For P see "SRIM"] | LET Effective (in Si) | Range (um) | Flux target (/cm²/s) | Fluence target (/cm²) | Duration Target (sec) | Beam Homogenity (%) | Type of test / Mode/SW tested... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 21 | OK | LT7101 - S1 (new) | 30 | 1A | 0 | 0 | Yes | C2*2 | Rh | 957 | 46 | 46 | 87 | 1.00E+03 | 1.00E+07 | 10000 | 10 | DSEE SoA. |
| 22 | 22 | OK | LT7101 - S2 (new) | 24 | 1A | 0 | 0 | Yes | C2*2 | Rh | 957 | 46 | 46 | 87 | 1.00E+04 | 1.00E+07 | 1000 | 10 | DSEE SoA. |
| 23 | 23 | OK | LT7101 - S3 (new) | 19 | 1A | 0 | 0 | Yes | C2*2 | Rh | 957 | 46 | 46 | 87 | 1.00E+04 | 1.00E+07 | 1000 | 10 | DSEE SoA. |
| 24 | 24 | OK | LT7101 - S4 (new) | 19 | 1A | 0 | 0 | Yes | C2*2 | Rh | 957 | 46 | 46 | 87 | 1.50E+04 | 1.00E+07 | 666.7 | 10 | DSEE SoA. |
| 33 | 33 | OK | LT7101 - S4 (new) | 19 | 2A | 0 | 0 | Yes | C2*2 | Xe | 995 | 63 | 63 | 73 | 1.50E+04 | 1.00E+07 | 666.7 | 10 | DSEE SoA. |
| 34 | 34 | OK | LT7101 - S3 (new) | 15 | 2A | 0 | 0 | Yes | C2*2 | Xe | 995 | 63 | 63 | 73 | 1.50E+04 | 1.00E+07 | 666.7 | 10 | DSEE SoA. |
| 35 | 35 | OK | LT7101 - S5 (new) | 15 | 2A | 0 | 0 | Yes | C2*2 | Xe | 995 | 63 | 63 | 73 | 1.50E+04 | 1.00E+07 | 666.7 | 10 | DSEE SoA. |
| 39 | 1 | OK | LT7101 - S6 | 15 | 1A | 0 | 0 | Yes | C2*2 | Xe | 995 | 63 | 63 | 73 | 1.50E+04 | 1.00E+07 | 666.7 | 10 | Confirmation run |
| 63 | 25 | OK | LT7101 - S5* | 12V, then 15V, then 19V. | 1A | 90 | 45 | Yes | C2*2 | Rh | 957 | 46 | 65 | 87 | 1.50E+04 | 1.00E+07 | 666.7 | 10 | Testing with tilt 45 and pitch 90° |

| Run | Scope Trigger | SEL current threshold (mA) | nominal current (mA) | Start time | Duration actual (sec) | Fluence actual (/cm²) | Cumulative Fluence (/cm²) | Flux actual (/cm²/s) | Run dose (krad) | Total dose (krad) | Test OK/ NOK | Measured SEL level w/o protection (mA) | # NDSEL (approximatively - to be postreated) | # DSEE (SEGR/SEB/DSEL) (approximatively) | # SET (approximatively) | # auto-SEFI (approximatively) | # soft-SEFI (approximatively) | # PC-SEFI (approximatively) | # Other SEE (approximatively) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | Vout pos. @ 5.3V | 700 | 130.00 | 18:30 | 213 | 8.63E+04 | 8.63E+04 | 405.16432 | 6.37E-02 | 6.37E-02 | OK | | | 1 DSEE | | | | | |
| 22 | Vout pos. @ 5.3V | 700 | 130.00 | 18:36 | 595 | 5.04E+05 | 5.04E+05 | 847.05882 | 3.72E-01 | #REF! | OK | | | | | | | | |
| 23 | Vout pos. @ 5.3V, then PG neg @ 0.2V. | 700 | 200.00 | 18:47 | | 1.00E+07 | 1.00E+07 | #DIV/0! | 7.38E+00 | #REF! | OK | | | SEL: 5 | | | 2 | | |
| 24 | Vout neg. @ 4.5V | 700 | 200.00 | 19:40 | 662 | 1.00E+07 | 1.00E+07 | 15105.74 | 7.38E+00 | 7.38E+00 | OK | | | SEL: 10 | | | 0 | | |
| 33 | Vout pos. @ 5.5V | 400 | 200.00 | 22:30 | 260 | 2.38E+06 | 2.38E+06 | 9153.8462 | 2.38E+00 | 2.38E+00 | OK | | | SEL: 7 (at SELth twice) | | | | | |
| 34 | Vout pos. @ 5.5V | 400 | 260.00 | 22:38 | 575 | 2.39E+06 | 2.39E+06 | 4156.5217 | 2.39E+00 | 2.39E+00 | OK | | | SEL: 7+2 (at the same time)+ 15 | | | 0 | | |
| 35 | Vout pos. @ 5.5V | 400 | 250.00 | 22:50 | 848 | 1.00E+07 | 1.00E+07 | 11792.453 | 1.00E+01 | 1.00E+01 | OK | | | SEL: 19+8+29 | | | 0 | | |
| 39 | Vout pos. @ 5.5V | 400 | 215.00 | 12:23 | 957 | 1.00E+07 | 1.00E+07 | 10449.321 | 1.00E+01 | 1.00E+01 | OK | | | SEL: 2 | | | | 7 then too many to count | |
| 63 | Vout pos. @ 5.5V | 1000 | 420.00 | 20:03 | 1174 | 6.90E+06 | 6.90E+06 | 5877.3424 | 5.09E+00 | 5.09E+00 | OK | | | | | | | 1 | |