Radiation Report

TRF0208-SEP, Near-DC to 11GHz, Fully Differential RF Amplifier Single-Event Effects (SEE) Radiation Report

ABSTRACT

The effect of heavy-ion irradiation on the single-event effects performance of the radiation-tolerant TRF0208-SEP is summarized in this report. Heavy-ions with an LET_{EFF} up to 56.1 MeV-cm^2/mg were used to irradiate three production devices in 12 runs. Flux up to 10^6 ions/cm^2-s and fluences up to 10^7 ions/cm^2 at temperatures of 25°C (SET) and 125°C (SEL), were used for the characterization. Results demonstrate that the TRF0208-SEP is SEL-free up to LET_{EFF} = 56.1 MeV-cm^2/mg and 125°C, and the cross section for the SET is discussed.

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1 Overview

The TRF0208-SEP is a very high performance, radiation hardened RF amplifier optimized for radio frequency (RF) applications. This device is an excellent choice for ac-coupled applications that require a single-ended to differential conversion when driving an analog-to-digital converter (ADC) such as the high performance ADC12DJ5200-SEP. The on-chip matching components simplify printed circuit board (PCB) implementation and provide the highest performance over the usable bandwidth. The device is fabricated in Texas Instruments' advanced complementary BiCMOS process and is available in a space-qualified, WQFN-FCRLF package. The device operates on a 3.3V single-rail supply. A power-down feature is also available for power savings.

For more detailed technical specifications, user-guides, and application notes visit: http://www.ti.com/product/TRF0208-SEP.

Table 1-1. Overview Information

Description	Device Information
TI Part Number	TRF0208-SEP
Device Function	Fully Differential Amplifier
Technology	BiCMOS
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy-Ion Fluence per Run	10^7 (for SEL and SET) ions/cm^2
Irradiation Temperature	25°C and 125°C (for SEL testing)

2 Single-Event Effects

The primary concern for the TRF0208-SEP is the resilience against the destructive single-event effects (DSEE), such as single-event latch-up (SEL) and single-event-burnout (SEB). Since the operating voltage of TRF0208-SEP is relatively low, 3.3V, SEB is not a concern.

The TRF0208-SEP was characterized for SEL events. In mixed technologies, such as the CBi-CMOS process used for the TRF0208-SEP, the presence of the CMOS circuitry introduces a potential SEL susceptibility. SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-substrate and n-well and n+ and p+ contacts) [1] [2]. If formed, the parasitic bipolar structure creates a high-conductance path (creating a steady-state current that is orders-of-magnitude higher than the normal operating current) between power and ground that persists (is "latched") until power is removed or until the device is destroyed by the high-current state. The TRF0208-SEP exhibited no SEL with heavy-ions of up to LET_{EFF} = 56.1 MeV-cm^2/mg at fluences in excess of 10^7 ions/cm^2 and a die temperature of 125°C.

Another concern on high reliability and performance applications is the single-events-transient (SET) characteristic of the device. The TRF0208-SEP SET performance was characterized up to LET_{EFF} = 56.1 MeV-cm^2/mg. The device was characterized for SET at supply voltage +3.3V under AC input conditions. Test conditions and results are discussed in Section 8.

3 Test Device and Evaluation Board Information

The TRF0208-SEP is packaged in a 12-pin RPV, WQFN - Flip Chip RLF (WQFN-FCRLF, 12) package as shown in Figure 3-1. The TRF0208SEP-EVM evaluation board (EVM) was used to evaluate the single-events-effects (SEE) of the TRF0208-SEP. Top and bottom views of the evaluation board used for the radiation testing are shown in Figure 3-2. Schematic of the evaluation board used for radiation testing is shown in Figure 3-3. For more technical information about the TRF0208-SEP, see https://www.ti.com/product/TRF0208-SEP/technicaldocuments.

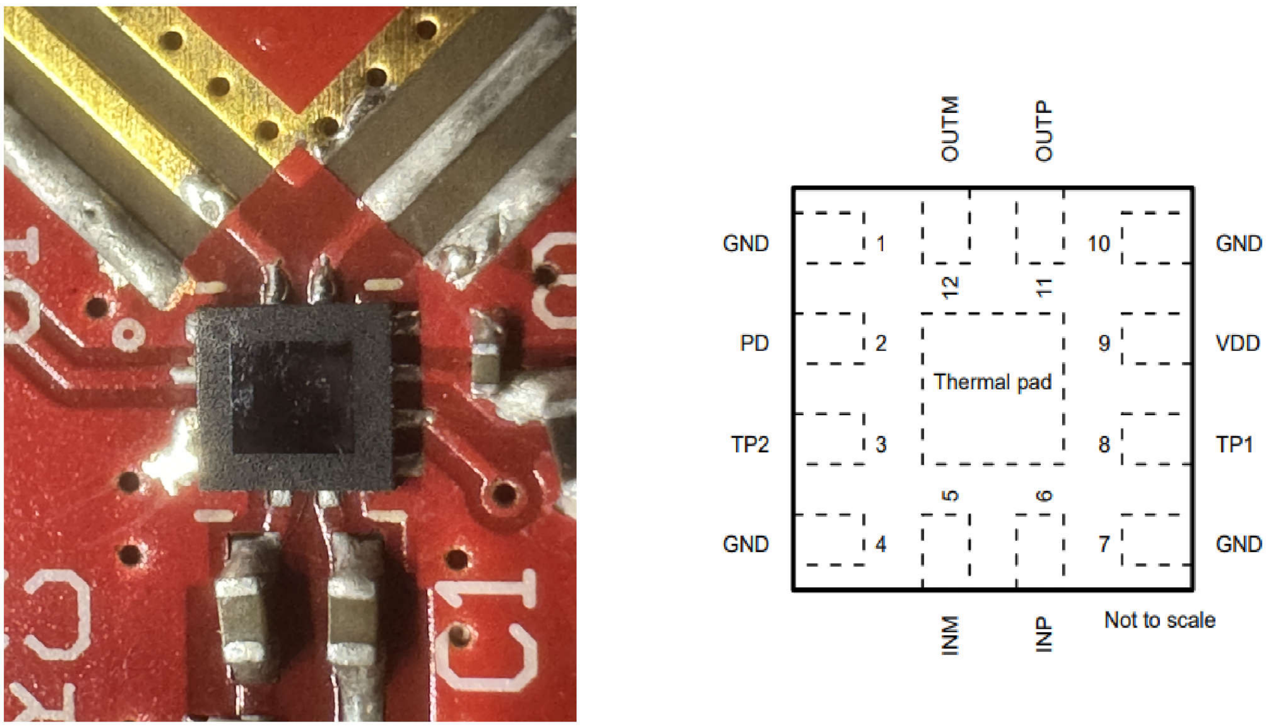

Figure 3-1. Decapped TRF0208-SEP (Left) and Device Pin Out (Right)

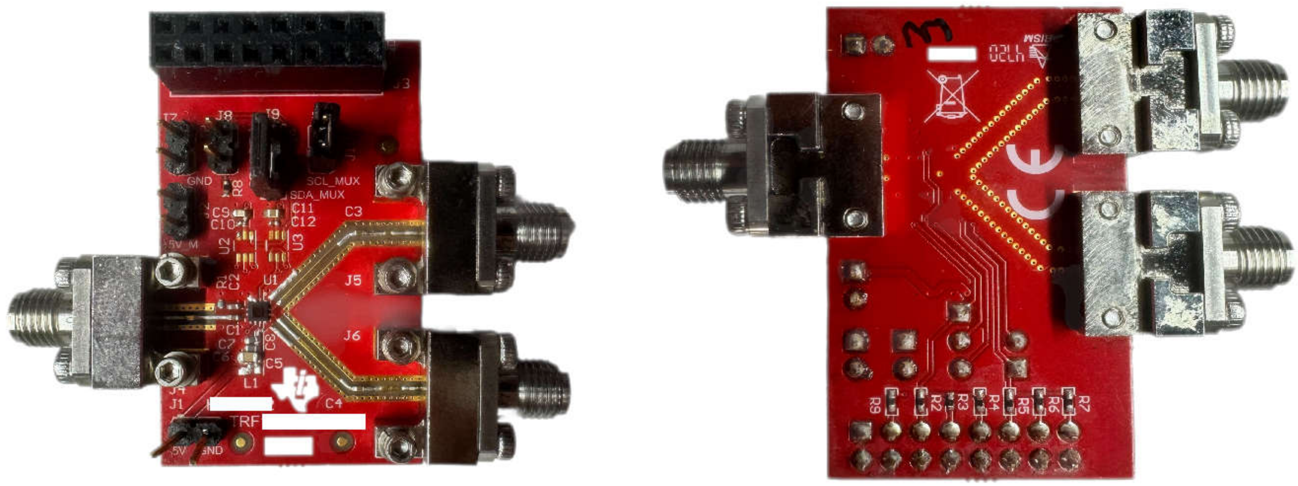

Figure 3-2. TRF0208SEP-EVM Board Top View (Left) and Bottom View (Right)

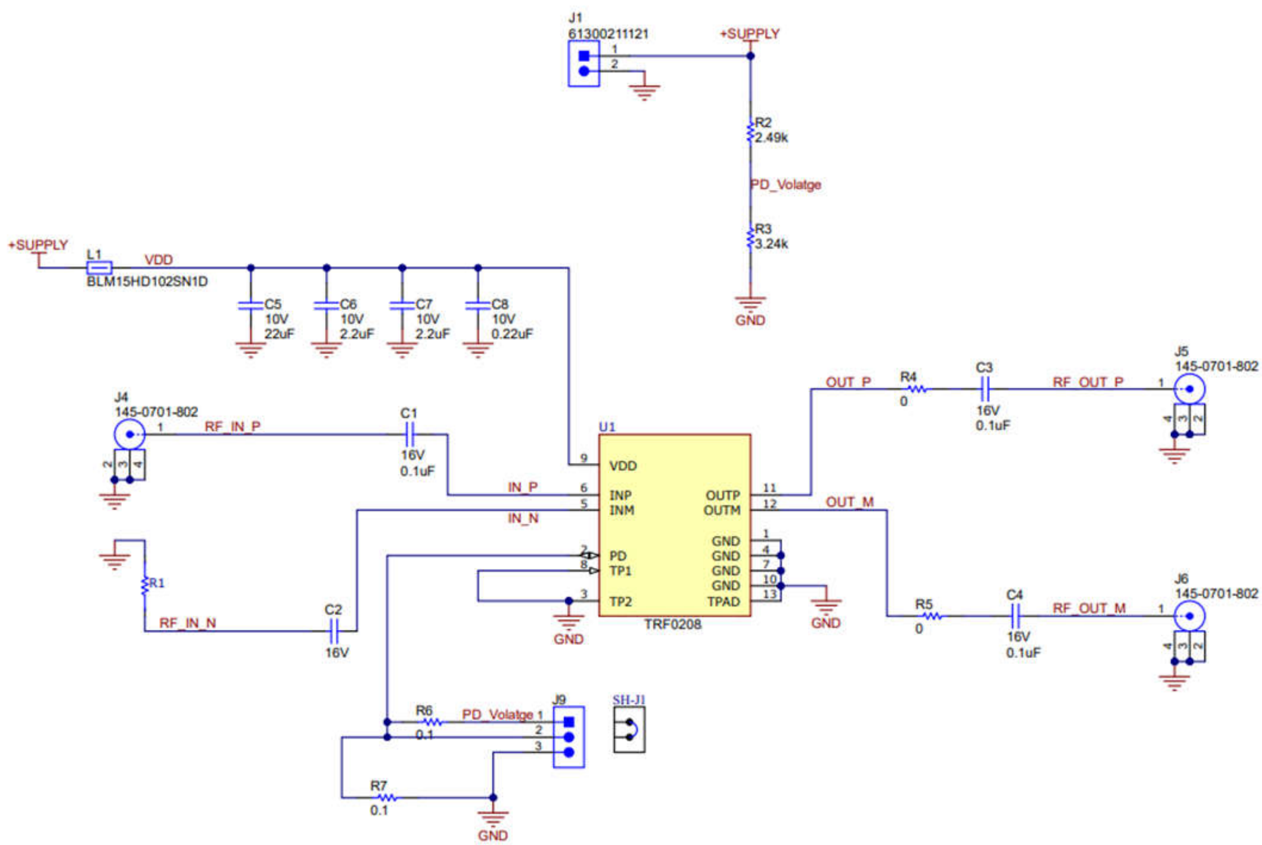

Figure 3-3. TRF0208SEP-EVM, Evaluation Module Board Schematic for SEE Testing

4 Irradiation Facility and Setup

The heavy-ion species used for the SEE studies on this product were provided and delivered by the Texas A&M University (TAMU) Cyclotron Radiation Effects Facility [4], using a superconducting cyclotron and advanced electron cyclotron resonance (ECR) ion source. At the fluxes used, ion beams had good flux stability and high-irradiation uniformity over a 1-in diameter circular cross-sectional area for the in-air station. Uniformity is achieved by means of magnetic defocusing. The flux of the beam is regulated over a broad range spanning several orders of magnitude. For the bulk of these studies ion fluxes between 10^4 and 10^5 ions/cm^2-s were used to provide a heavy-ion fluences between 10^6 and 10^7 ions/cm^2.

For these experiments Argon (^{40}Ar), Copper (^{63}Cu), Krypton (^{84}Kr), and Silver (^{107}Ag) were used. Angles were used to increment the LET_{EFF}, details are provided in Section 5. Ion beam uniformity for all tests was in the range of 88 to 97%.

Figure 4-1 shows the TRF0208-SEP mounted on the TRF0208SEP-EVM board in front of the beam exit port, as in the heavy-ion characterization. The beam port has a 1-mil Aramica (Kevlar®), 1-in diameter to allow in-air testing while maintaining the vacuum in the accelerator with only minor ion energy losses. The air space between the device-under-test (DUT) and the beam exit port was set to 40 mm (most used) and 60 mm.

The data recorded in this report was based on finalized EVM boards with optimized component values that follow data sheet recommendations.

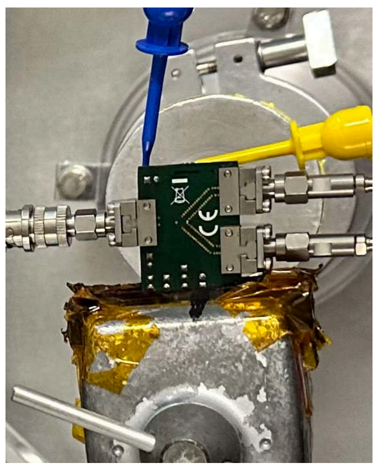

Figure 4-1. Decapped TRF0208-SEP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

5 Depth, Range, and LET_{EFF} Calculation

TRF0208-SEP is fabricated in the TI BiCMOS process and the die is packaged as a flip chip. The decapped unit exposes the silicon substrate directly when packaged in the flip-chip configuration. The units used were background to 50 microns, for proper ion penetration. The effective LET (LET_{EFF}), depth, and range were determined with the custom RADsim - IONS application (developed at Texas Instruments and based on the latest SRIM2013 [5] models). The applications accounts for energy loss through the 1-mil thick Aramica (DuPont® Kevlar®) beam port window and the air gap between the DUT and the heavy-ion exit port is 40mm. An image of the RADsim - IONS is shown in Figure 5-1 and the ions details are presented in Table 5-1.

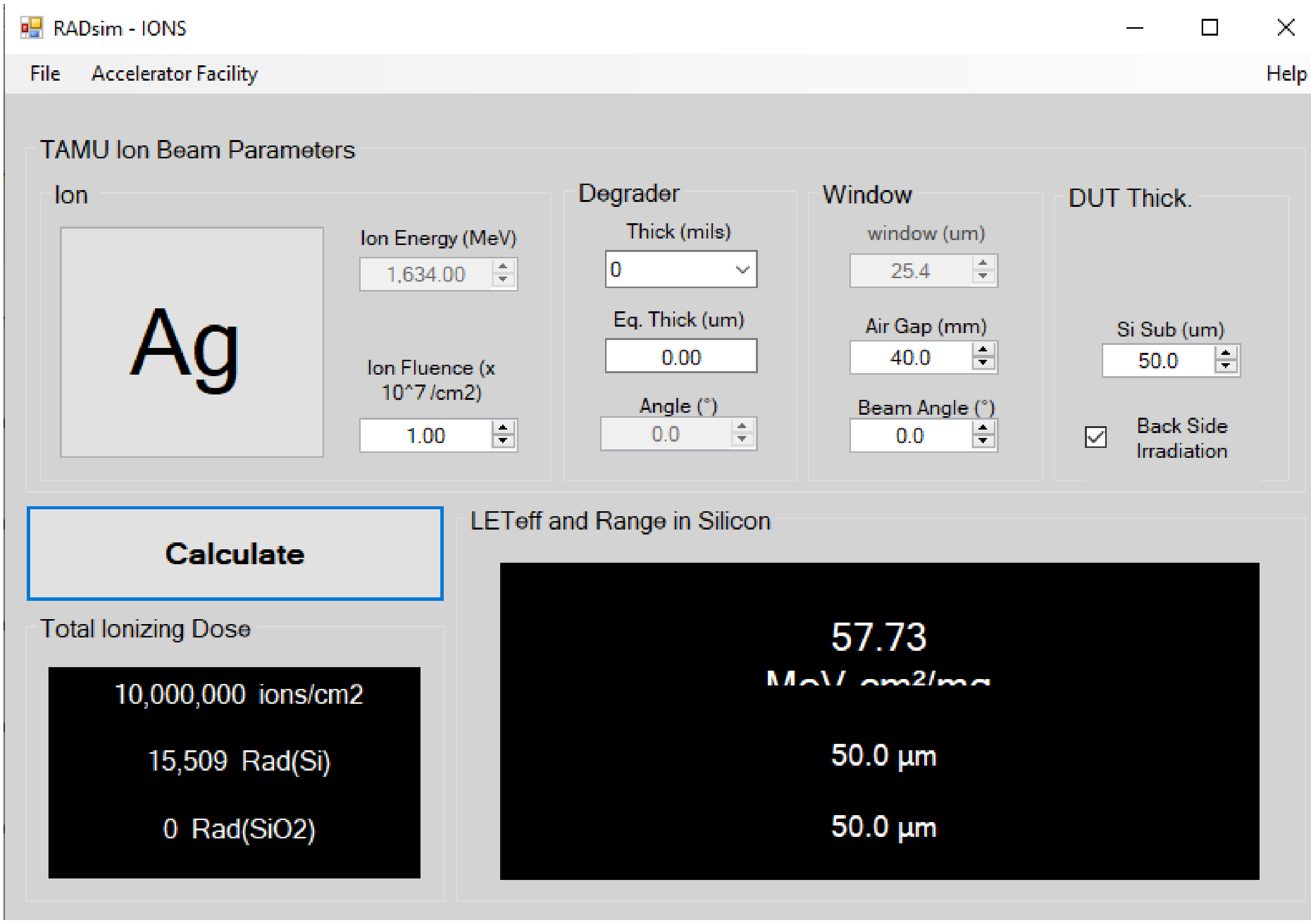

Figure 5-1. GUI of RADsim Application Used to Determine Key Ion Parameters

Table 5-1. LET_{EFF}, Depth, and Range for the Ions Used for SEE Characterization of the TRF0208-SEP

Ion Type	Angle of Incidence (°)	Depth in Silicon (µm)	Range in Silicon (µm)	LET_{EFF} (MeV-cm^2/mg)	Distance (mm)
Ar	0	50	50	9.75	40
Cu	0	50	50	24.54	40
Kr	0	50	50	36.1	40
Ag	0	50	50	57.73	40

6 Test Set-Up and Procedures

SEE testing was performed on a TRF0208-SEP device mounted on a TRF0208SEP-EVM. The device was provided power through J1 input (+SUPPLY = +3.45 V and GND) using the PXIe-4139 precision power supply in a 4-wire configuration. The TRF0208-SEP was evaluated with AC input signal provided on the INP input (J4). For the AC test, the input was driven onto the INP pin (J4) with R&S SME03 signal generator (capable of providing a 3GHz signal) using a high speed coaxial cable. Input frequency was set to 100MHz (most used), 500MHz, and 1GHz, the input amplitude was set in such way that the output was set to 800mV$_{P-P}$. Also during all time the PD pin (J9 jumper) was connected to GND.

The device was evaluated in differential mode. SETs where monitored using a Mixed Signal Oscilloscope, MSO58B (8 channel, 1GHz, 6.25GS/s, 62.5M record length). The differential output of the TRF0208-SEP is converted to single ended by using an Hyperlabs HL9402 balun and was monitored.

The power supply (PS) was controlled and monitored using a custom-developed LabView™ program (PXI-RadTest) running on a NI-PXIe-8135 controller. The R&S SME03 was controlled via the GPIB bus, using the stand alone LabView™ drivers. The MSO58B was controlled using its front-panel interface. The MSO was left in the cave at all times, to minimize the probe cable length. A keyboard, video, and mouse (KVM) extender was used to control and view the MSO from the control room at TAMU. A block diagram of the setup used for SEE testing the TRF0208-SEP is illustrated in Figure 6-1. Equipment settings and compliances used during the characterization are shown in Table 6-1. For the SEL testing the device was heated using a convection heat gun aimed at the die. The junction temperature was monitored by using a K-type thermocouple attached as close as possible to the die.

Table 6-1. Equipment Setup and Parameters Used for SEE Testing the TRF0208-SEP

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
VDD (J1)	NI PXIe-4139	3A	3A	3.3V, 3.45V, 3.7V
INP (J4)	R&S SME03	5KHz-3GHz	—	100MHz, 500MHz, 1GHz
OUTP (J6) and OUTM (J5)	Tektronix MSO58B	6.25GS/S	—	6.25 GS/s

All boards used for SEE testing were fully checked for functionality and dry runs performed to ensure that the test system was stable under all bias and load conditions prior to being taken to the TAMU facility. During the heavy-ion testing, the LabView™ control program powered up the TRF0208-SEP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability had been confirmed, the beam shutter was opened to expose the device to the heavy-ion beam. The shutter remained open until the target fluence was achieved (determined by external detectors and counters).

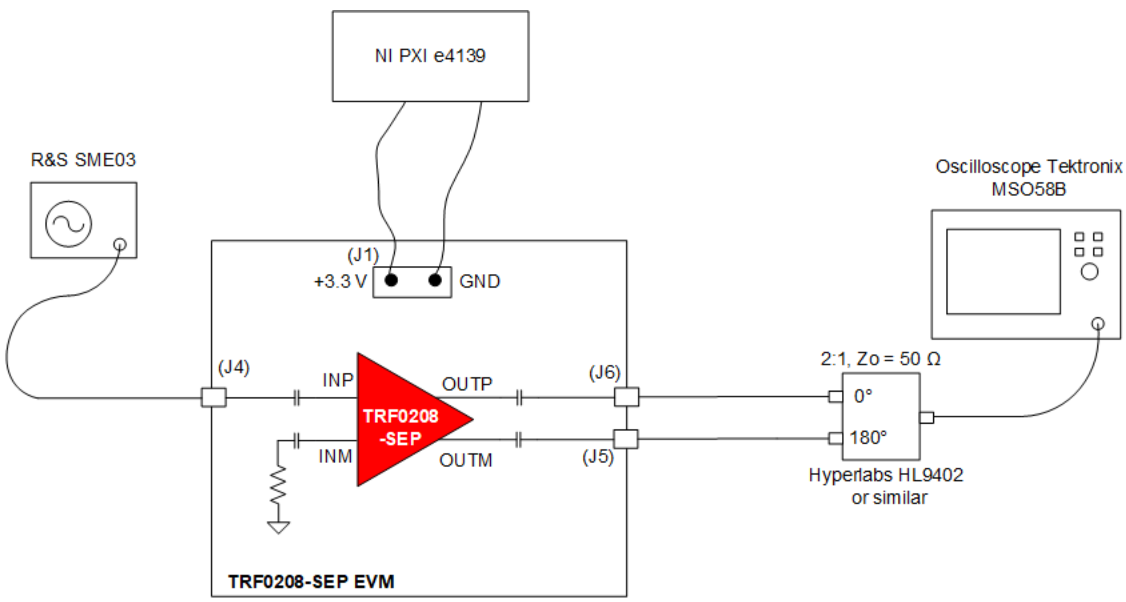

Figure 6-1. Block Diagram of the Test Setup Used for the TRF0208-SEP Mounted on a TRF0208SEP-EVM SEE Characterization

7 Single-Event Latch-up (SEL) Results

All SEL characterizations were performed with forced hot air to maintain the die temperature at 125°C during the tests. The device was exposed to a Silver (Ag) heavy-ion beam incident on the die surface at 0° incident angle for an effective LET of 56.1 MeV-cm^2/mg. A flux of 10^5 ions/cm^2-s and fluence of 10^7 ions/cm^2 per run was used in all three runs. The device was powered up with maximum supply voltage of +3.45 V in most runs. In few runs device was tested at absolute maximum supply voltage of +3.7 V. During all runs the device was actively amplifying a single ended input signal at 100 MHz. Both differential outputs were independently terminated (SE) to 50 Ω .

Time duration to achieve this fluence was approximately 2 minutes. The SEL results and conditions are summarized in Table 7-1. No SEL events were observed under any of the three test runs, indicating that the TRF0208SEP is SEL-immune at a die-exposed temperature of T = 125°C and LET = 56.1 MeV-cm^2/mg. A typical temperature and supply current vs time plot is shown on Figure 7-1.

Table 7-1. Summary of TRF0208-SEP SEL Results

Run #	Unit #	Die-Exposed Temp. (°C)	Ion Type	Incident Angle (°)	Fluence (ions/cm^2)	Average Flux (ions·cm²/mg)	V_{DD} (V)	Actual LET_{EFF} (MeV·cm²/mg)	Uniformity	Input Power (dBm)	Differential Output Load (Ω)	Differential Output Voltage (mV_{PP})	SEL Result
1	1	125	Ag (107)	0	1.0×10^7	1.0×10^5	3.45	56.1	93%	0	100	3000	Pass
2	1	125	Ag (107)	0	1.0×10^7	1.0×10^5	3.7	56.1	94%	0	100	3000	Pass
3	1	125	Ag (107)	0	3.0×10^7	1.0×10^5	3.45	56.1	93%	-14	100	1000	Pass
4	2	125	Ag (107)	0	1.0×10^7	1.0×10^5	3.45	56.1	93%	0	100	3000	Pass
5	2	125	Ag (107)	0	1.0×10^7	1.0×10^5	3.7	56.1	93%	0	100	3000	Pass
6	2	125	Ag (107)	0	3.0×10^7	1.0×10^5	3.45	56.1	93%	-14	100	1000	Pass
7	3	125	Ag (107)	0	1.0×10^7	1.0×10^5	3.45	56.1	93%	0	100	3000	Pass
8	3	125	Ag (107)	0	1.0×10^7	1.0×10^5	3.7	56.1	93%	0	100	3000	Pass
9	3	125	Ag (107)	0	3.0×10^7	1.0×10^5	3.45	56.1	93%	-14	100	1000	Pass

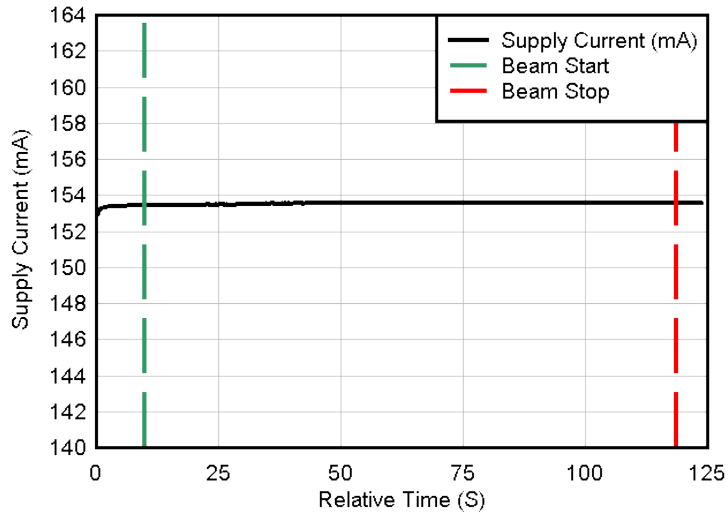

Figure 7-1. Supply Current versus Time Data for SEL Run #1 for the TRF0208-SEP

8 Single-Event Transients (SET) Results

The TRF0208-SEP was characterized for SETs from 9.62 to 56.1MeV-cm^2/mg (refer to Table 5-1) at +3.3V supply voltages. The device was tested at room temperature for all SETs runs. Since the TRF0208-SEP is a flip chip device, the devices were thinned to 50µm for proper heavy-ion penetration into the active circuits. Flux of 10^5 and 10^6 (most used) ions/cm^2-s and fluences of 10^6 and 10^7 (most used) ions/cm^2 per run were used during the heavy ion characterization. The devices were tested under dynamic (AC) inputs (as described in Section 6). The SETs discussed on this report were defined as output voltages excursion that exceed a window trigger set on the MSO58B. Outputs of the TRF0208-SEP were converted to SE using HL9402 balun and monitored. Test conditions used during the testing are presented in Table 8-1. Weibull-Fit and cross section for DUT #2 and DUT#3 are presented in Figure 8-1. To calculate the cross section values at different supply voltages the total number of upsets (or transients) and the fluences where combined (add together) by LET_{EFF} to calculate the upper bound cross section (as discussed in Appendix B) at 95% confidence interval. The $\sigma_{PERCASE}$ cross section presented in the summary tables, was calculated using the MTBF method at 95% confidence. For the SET test upsets were observed when setting the trigger to ±20 mV and monitoring the output of the balun. Worst case AC upset for each leg is shown in Figure 8-2. Though not observed during the testing, note that an SET event can result in output going up to saturation voltage.

The upper-bound SET cross-sections (σ_{ALL}) was calculated using the events and fluences. Using the MTBF method at 95% confidence interval (see Appendix B for a discussion of the MTBF cross section calculation method), the combined upper bound cross section is:

$\sigma_{SET\text{-}ALL\text{-}AC\text{-}DIFF} \leq 4.5 \times 10^{-6}$cm^2/device at LET = 57.1MeV-cm^2/mg, T = 25°C, 95% conf. and V_{DD} = +3.3V

Table 8-1. Summary of the TRF0208-SEP AC Tests at V_{DD} = 3.3V

Run #	Unit #	Test Type	Die-Exposed Temp. (°C)	Ion Type	LET_{EFF} (MeV·cm²/mg)	Average Flux (ions·cm²/mg)	Fluence (# of ions)	Uniformity	Trigger Value	#Events
1	4	SET	25	Ag	56.1	9.87E+04	1.00E+07	95%	UL = +20mV LL = –20mV	31
2	4	SET	25	Ag	56.1	1.10E+04	1.00E+07	95%	UL = +20mV LL = –20mV	32
3	4	SET	25	Kr	35.2	1.05E+05	9.95E+06	95%	UL = +20mV LL = –20mV	20
4	4	SET	25	Kr	35.2	5.03E+04	1.00E+07	95%	UL = +20mV LL = –20mV	18

Table 8-1. Summary of the TRF0208-SEP AC Tests at V_{DD} = 3.3V (continued)

Run #	Unit #	Test Type	Die-Exposed Temp. (°C)	Ion Type	LET_{EFF} (MeV·cm²/mg)	Average Flux (ions·cm²/mg)	Fluence (# of ions)	Uniformity	Trigger Value	#Events
5	4	SET	25	Cu	24	1.04E+05	9.95E+06	95%	UL = +20mV LL = –20mV	3
6	4	SET	25	Cu	24	5.09E+04	1.00E+07	95%	UL = +20mV LL = –20mV	4
7	4	SET	25	Ar	9.62	1.00E+05	1.00E+07	95%	UL = +20mV LL = –20mV	0
8	4	SET	25	Ar	9.62	4.91E+04	1.00E+07	92%	UL = +20mV LL = –20mV	0

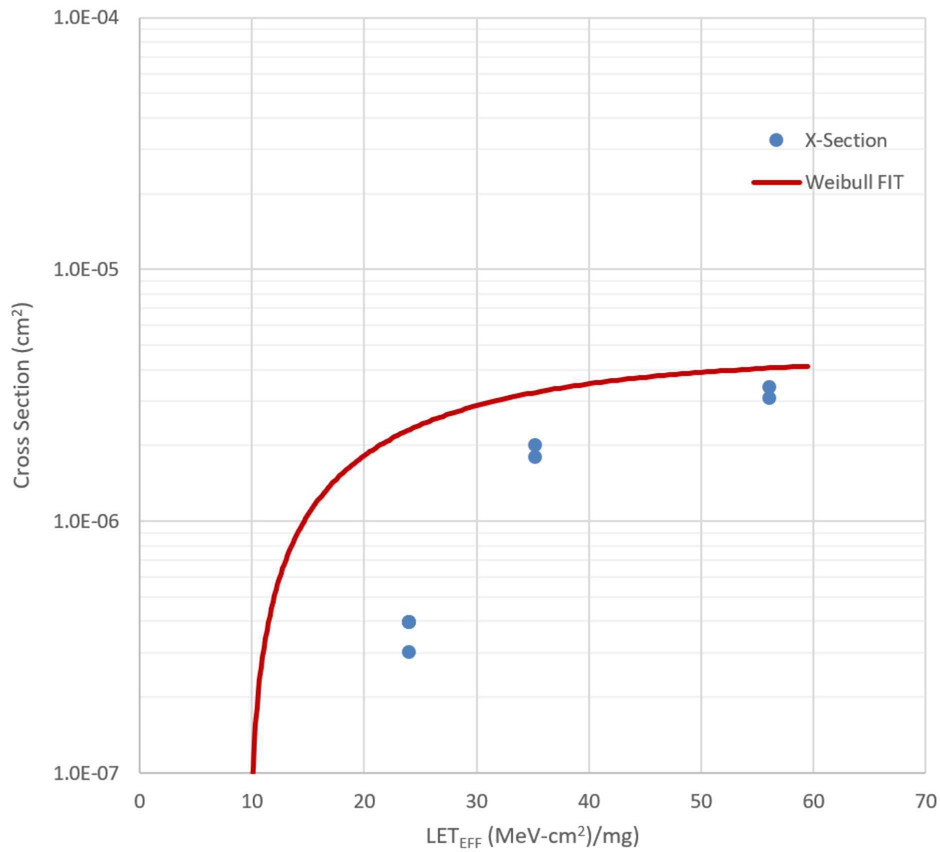

Figure 8-1. Cross Section and Weibull-Fit for DUT #4

$$\sigma = \sigma_{SAT} \times \left(1 - e^{-\left(\frac{LET - Onset}{W}\right)^{S}}\right) \tag{1}$$

Table 8-2. Weibull-FIT Parameters for SET, AC Test at Supply Voltage of +3.3V

Parameter	Value
Onset (MeV-cm^2/mg)	9.62
σ_{SAT} (cm^2)	4.5×10^{-6}
W	20
s	1

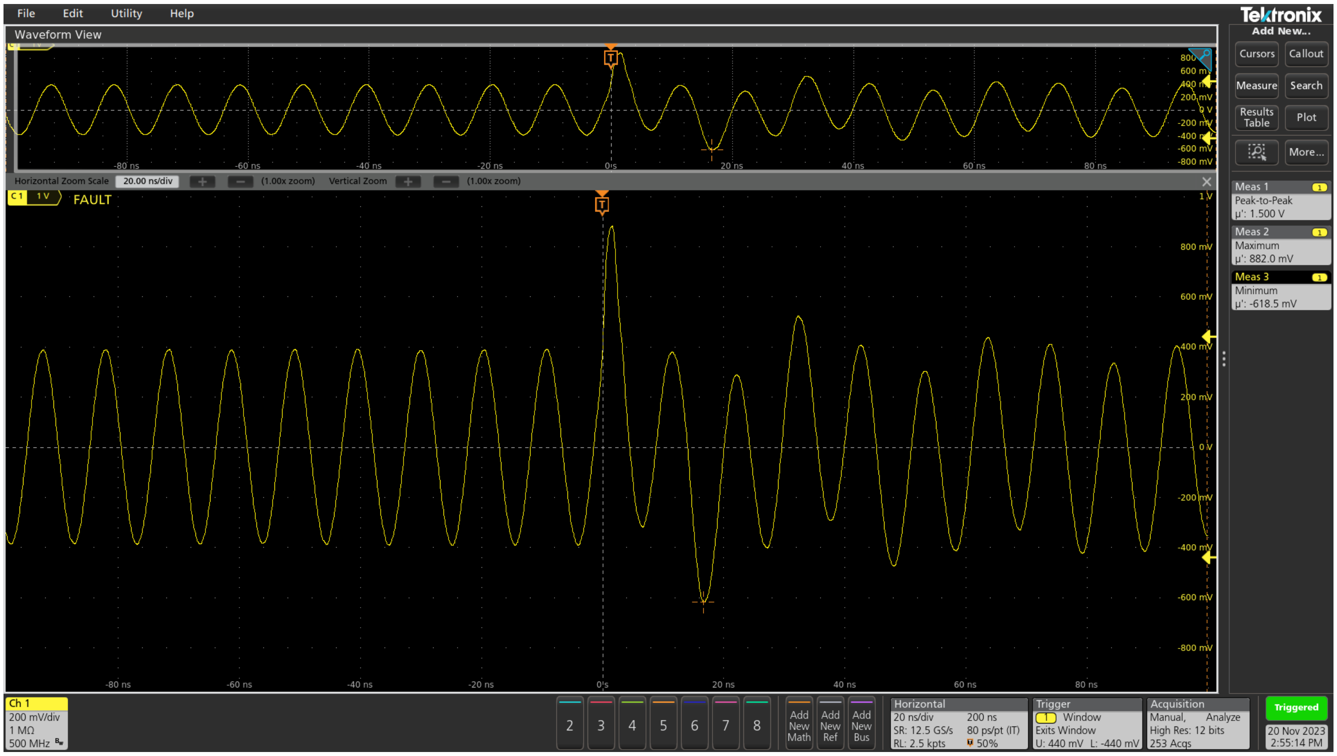

Figure 8-2. Worst Case Upset in AC Test When Monitoring Differential Output of the TRF0208-SEP

9 Event Rate Calculations

Event rates were calculated for LEO (ISS) and GEO environments by combining CREME96 orbital integral flux estimations and simplified SEE cross-sections according to methods described in *Heavy Ion Orbital Environment Single-Event Effects Estimations*. We assume a minimum shielding configuration of 100 mils (2.54 mm) of aluminum, and "worst-week" solar activity (this is similar to a 99% upper bound for the environment). Using the 95% upper-bounds for the SET the event-rates of the TRF0208-SEP are tabulated in Table 9-1.

Table 9-1. SET Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET (MeV·cm²/mg)	CREME96 Integral Flux (/day·cm²)	σ SAT (cm²)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	9.62	36.4	4.5×10^{-6}	3.12×10^{-6}	129.809	879.406
GEO		301		2.45×10^{-5}	1019.52	111.969

10 Summary

The purpose of this study was to characterize the effect of heavy-ion irradiation on the single-event effect (SEE) performance of the TRF0208-SEP 11GHz, fully differential, ADC driver RF amplifier. Extensive SEE testing with heavy-ions having LET_{EFF} from 9.62 to 56.1MeV-cm^2/mg were conducted with heavy-ion fluences ranging from 10^6 to 10^7 ions/cm^2 per run, at two different voltages and input conditions. The SEE results demonstrated that the TRF0208-SEP is SEL-free up to LET_{EFF} = 56.1MeV-cm^2/mg. CREME96-based worst-week event-rate calculations for LEO (ISS) and GEO orbits clearly demonstrate the robustness of the TRF0208-SEP in two harshly conservative space environments.

A Total Ionizing Dose from SEE Experiments

The production TRF0208-SEP POL is rated to a total ionizing dose (TID) of 50 krad(Si). In the course of the SEE testing, the heavy-ion exposures delivered ≈ 1 krad(Si) per 10^6 ions/cm^2 run. The cumulative TID exposure for each device respectively, over all runs they each underwent, was determined to be greater than 50 krad(Si). The three production TRF0208-SEP devices used in the studies described in this report stayed within specification and were fully-functional after the heavy-ion SEE testing was completed.

B Confidence Interval Calculations

For conventional products where hundreds of failures are seen during a single exposure, one can determine the average failure rate of parts being tested in a heavy-ion beam as a function of fluence with high degree of certainty and reasonably tight standard deviation, and thus have a good deal of confidence that the calculated cross-section is accurate.

With radiation hardened parts however, determining the cross-section becomes more difficult since often few, or even, no failures are observed during an entire exposure. Determining the cross-section using an average failure rate with standard deviation is no longer a viable option, and the common practice of assuming a single error occurred at the conclusion of a null-result can end up in a greatly underestimated cross-section.

In cases where observed failures are rare or non-existent, the use of confidence intervals and the chi-squared distribution is indicated. The Chi-Squared distribution is particularly good for the determination of a reliability level when the failures occur at a constant rate. In the case of SEE testing, where the ion events are random in time and position within the irradiation area, one expects a failure rate that is independent of time (presuming that parametric shifts induced by the total ionizing dose do not affect the failure rate), and thus the use of chi-squared statistical techniques is valid (since events are rare an exponential or Poisson distribution is usually used).

In a typical SEE experiment, the device-under-test (DUT) is exposed to a known, fixed fluence (ions/cm^2) while the DUT is monitored for failures. This is analogous to fixed-time reliability testing and, more specifically, time-terminated testing, where the reliability test is terminated after a fixed amount of time whether or not a failure has occurred (in the case of SEE tests fluence is substituted for time and hence this is a fixed fluence test) [5]. Calculating a confidence interval specifically provides a range of values which is likely to contain the parameter of interest (the actual number of failures/fluence). Confidence intervals are constructed at a specific confidence level. For example, a 95% confidence level implies that if a given number of units were sampled numerous times and a confidence interval estimated for each test, the resulting set of confidence intervals brackets the true population parameter in about 95% of the cases.

To estimate the cross-section from a null-result (no fails observed for a given fluence) with a confidence interval, we start with the standard reliability determination of lower-bound (minimum) mean-time-to-failure for fixed-time testing (an exponential distribution is assumed):

$$MTTF = \frac{2nT}{\chi^2_{2(d+1);100\left(1-\frac{\alpha}{2}\right)}} \quad (2)$$

Where *MTTF* is the minimum (lower-bound) mean-time-to-failure, *n* is the number of units tested (presuming each unit is tested under identical conditions) and *T*, is the test time, and x^2 is the chi-square distribution evaluated at 100 (1 – σ / 2) confidence level and where d is the degrees-of-freedom (the number of failures observed). With slight modification for our purposes we invert the inequality and substitute *F* (fluence) in the place of *T*:

$$MFTF = \frac{2nF}{\chi^2_2\left(d+1\right); 100\left(1-\frac{\alpha}{2}\right)} \quad (3)$$

Where now *MFTF* is mean-fluence-to-failure and *F* is the test fluence, and as before, x^2 is the chi-square distribution evaluated at 100 (1 – σ / 2) confidence and where *d* is the degrees-of-freedom (the number of failures observed). The inverse relation between MTTF and failure rate is mirrored with the MFTF. Thus the upper-bound cross-section is obtained by inverting the MFTF:

$$\sigma = \frac{\chi^2_2\left(d+1\right); 100\left(1-\frac{\alpha}{2}\right)}{2nF} \quad (4)$$

Let's assume that all tests are terminated at a total fluence of 10^6 ions/cm^2. Let's also assume that we have a number of devices with very different performances that are tested under identical conditions. Assume a 95% confidence level (σ = 0.05). Note that as *d* increases from 0 events to 100 events the actual confidence interval becomes smaller, indicating that the range of values of the true value of the population parameter (in this case the cross-section) is approaching the mean value + 1 standard deviation. This makes sense when one considers that as more events are observed the statistics are improved such that uncertainty in the actual device performance is reduced.

Table B-1. Experimental Example Calculation of Mean-Fluence-to-Failure (MFTF) and σ Using a 95% Confidence Interval

Degrees-of-Freedom (d)	2(d + 1)	χ^2 at 95%	Calculated Cross-Section (cm^2)		
			Upper-Bound at 95% Confidence	Mean	Average + Standard Deviation
0	2	7.38	3.69E–06	0.00E+00	0.00E+00
1	4	11.14	5.57E–06	1.00E–06	2.00E–06
2	6	14.45	7.22E–06	2.00E–06	3.41E–06
3	8	17.53	8.77E–06	3.00E–06	4.73E–06
4	10	20.48	1.02E–05	4.00E–06	6.00E–06
5	12	23.34	1.17E–05	5.00E–06	7.24E–06
10	22	36.78	1.84E–05	1.00E–05	1.32E–05
50	102	131.84	6.59E–05	5.00E–05	5.71E–05
100	202	243.25	1.22E–04	1.00E–04	1.10E–04

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