Radiation Report

TRF0213-SEP, Radiation-Tolerant, Near-DC to >14GHz, Single-Ended-to-Differential RF Amp Single-Event Effects Radiation Report

ABSTRACT

The effect of heavy-ion irradiation on the single-event effects performance of the radiation-tolerant TRF0213-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 TRF0213-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 TRF0213-SEP is a high-performance, radiation-tolerant 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 5V single-rail supply. A power-down feature is also available for power savings.

For more detailed technical specifications, user-guides, and application notes visit the TRF0213-SEP product page.

Table 1-1. Overview Information

Description	Device Information
TI Part Number	TRF0213-SEP
Device Function	Single-Ended-to-Differential RF Amplifier
Technology	BICMOS
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy-Ion Fluence per Run	1 x 10^7, 2 x 10^7 ions/cm^2 (SEL) and 2 x 10^6 ions/cm^2 (SET)
Irradiation Temperature	25°C (for SET testing) and 125°C (for SEL testing)

2 Single-Event Effects

The primary concern for the TRF0213-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 TRF0213-SEP is relatively low, 5V, SEB is not a concern.

The TRF0213-SEP was characterized for SEL events. In mixed technologies, such as the Bi-CMOS process used for the TRF0213-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 TRF0213-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 TRF0213-SEP SET performance was characterized up to LET_{EFF} = 56.1 MeV-cm^2/mg. The device was primarily characterized for SET at a typical recommended operating supply voltage of +5V and information-only up to an absolute maximum voltage of +5.5V under AC input conditions. Test conditions and results are discussed in Section 8.

3 Test Device and Evaluation Board Information

The TRF0213-SEP is packaged in a 12-pin RPV, WQFN - Flip Chip RLF (WQFN-FCRLF, 12) package as shown in Figure 3-1. The TRF0213SEP-EVM evaluation board (EVM) was used to evaluate the single-events-effects (SEE) of the TRF0213-SEP. Top view of the evaluation board used for the radiation testing in 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 TRF0213-SEP, see TRF0213-SEP's technical documents.

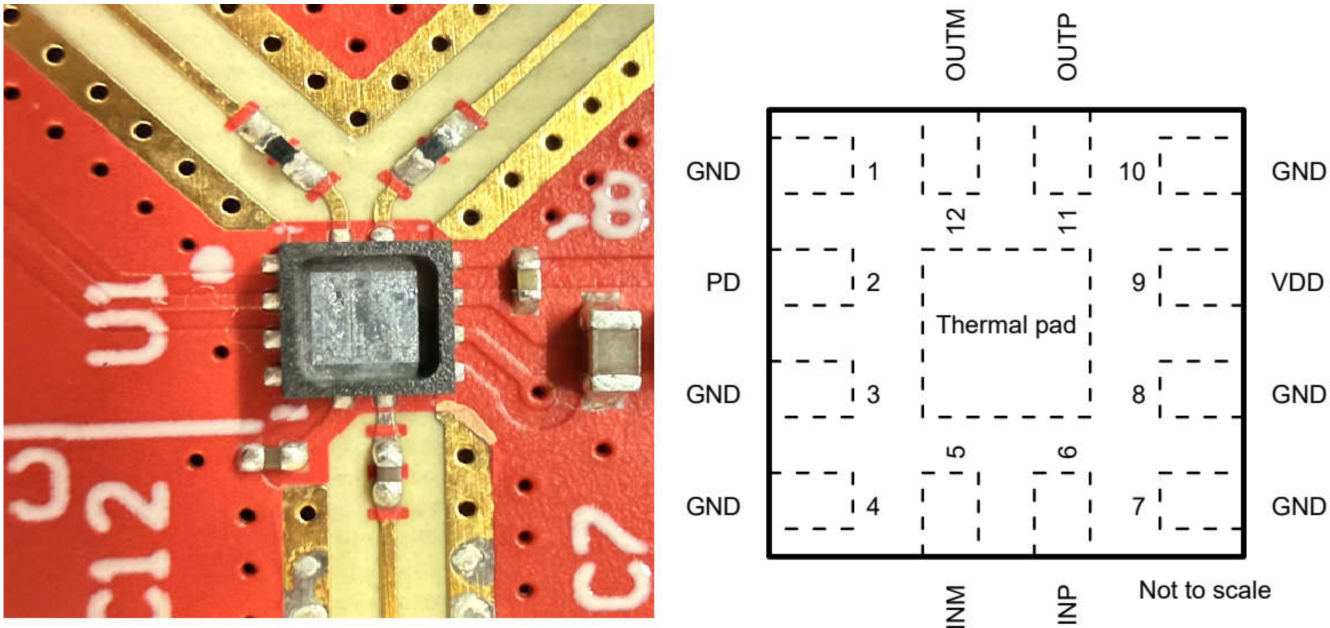

Figure 3-1. Decapped TRF0213-SEP (Left) and Device Pin Out (Right)

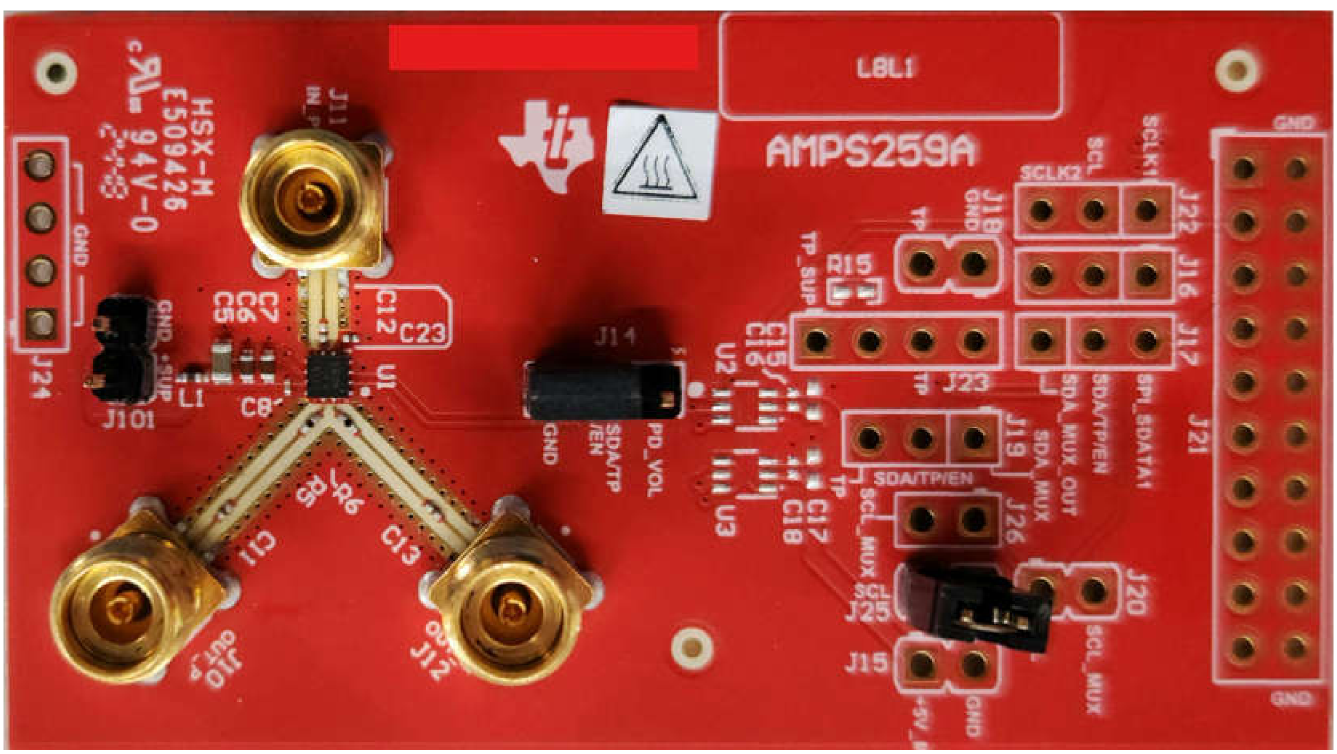

Figure 3-2. TRF0213SEP-EVM Board Top View

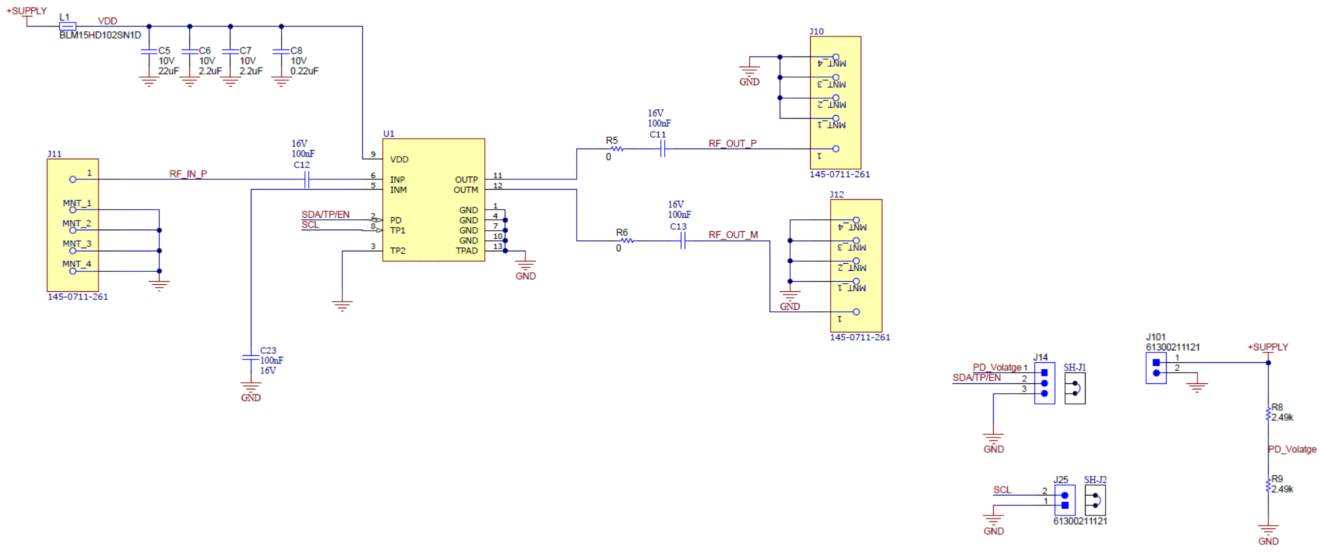

Figure 3-3. TRF0213SEP-EVM, Evaluation Module Board Schematic for SEE Testing

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 1in 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 TRF0213-SEP mounted on the TRF0213SEP-EVM board in front of the beam exit port, as in the heavy-ion characterization. The beam port has a 1-mil Aramica (Kevlar), 1in 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 40mm.

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

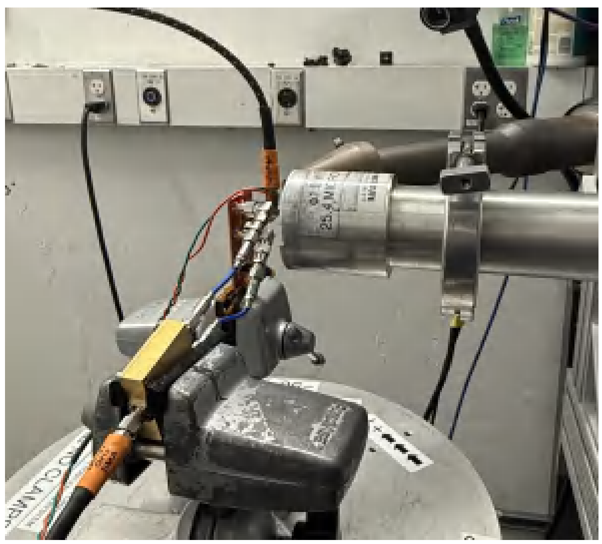

Figure 4-1. Decapped TRF0213-SEP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

5 Depth, Range, and LET$_{EFF}$ Calculation

TRF0213-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.

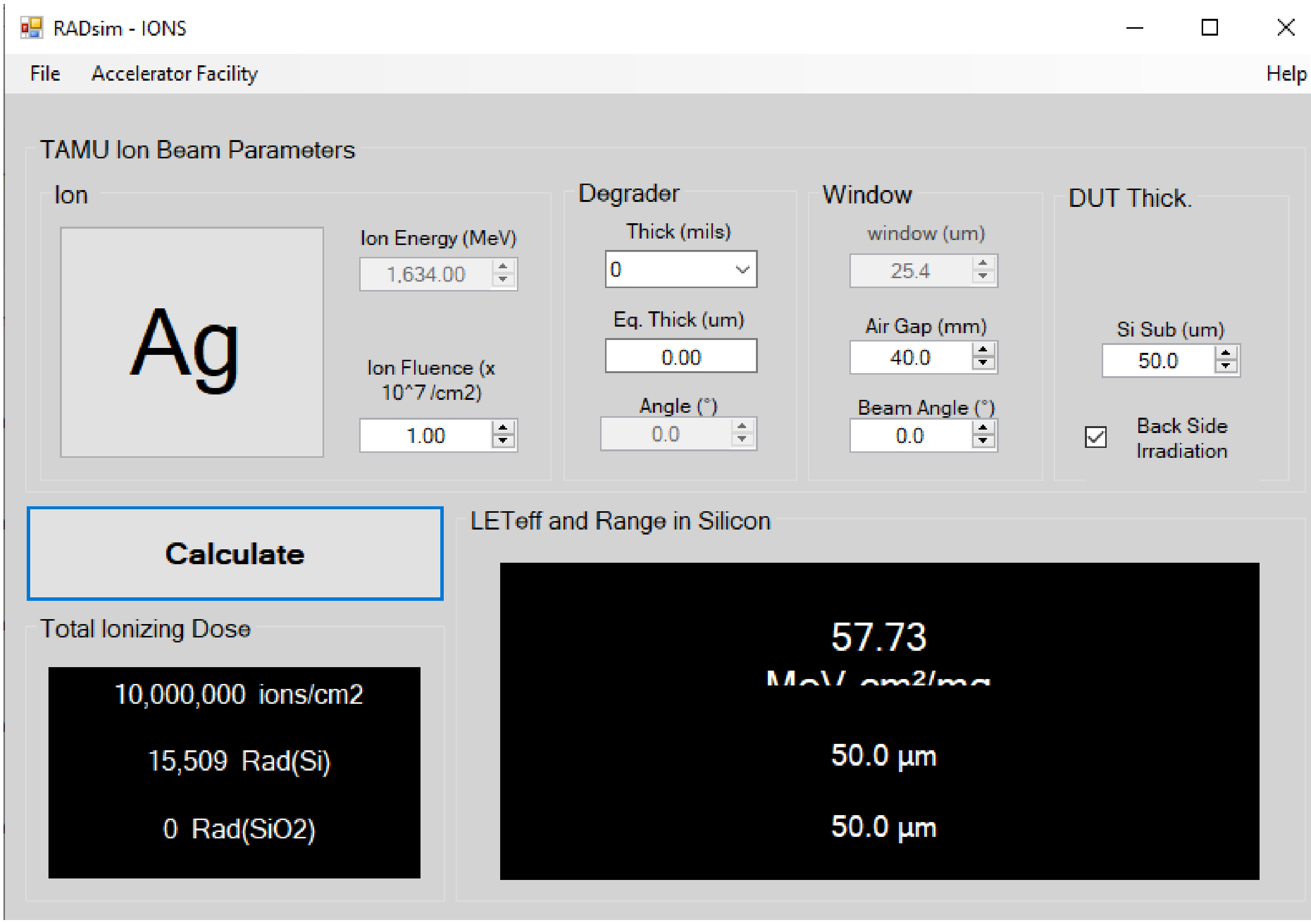

Figure 5-1. GUI of RADsim Application Used to Determine Key Ion Parameters

Table 5-1. LET$_{EFF}$, Depth, and Range for the Ions Used for SEE Characterization of the TRF0213-SEP

Ion Type	Angle of Incidence (°)	Depth in Silicon (µm)	Range in Silicon (µm)	LET$_{EFF}$ (MeV-cm^2/mg)	Distance (mm)
N(14)	0	50	50	1.42	40
Ne(20)	0	50	50	3.01	40
Ar(40)	0	50	50	9.75	40
Cu(63)	0	50	50	24.54	40
Kr(84)	0	50	50	36.1	40
Ag(109)	0	50	50	57.73	40

6 Test Set-Up and Procedures

SEE testing was performed on a TRF0213-SEP device mounted on a TRF0213SEP-EVM. The device was provided power through J101 input (+SUPPLY = +5.25V and GND) using the PXIe-4139 precision power supply in a 4-wire configuration. The TRF0213-SEP was evaluated with AC input signal provided on the INP input (J11). For the AC test, the input was driven onto the INP pin (J11) with R&S SGS100A signal generator (capable of providing a 6GHz signal) using a high speed coaxial cable. Input frequency was set to 500MHz, the input amplitude was set in a way that the output as measured on the oscilloscope was $500mV_{PP}$. The PD pin (J14 jumper) was connected to GND during the testing.

The device was evaluated in differential mode. SEEs where monitored using a Mixed Signal Oscilloscope, MSO58B (8-channel, 1GHz, 25GS/s, 62.5M record length). The differential output of the TRF0213-SEP is converted to single ended using a Hyperlabs HL9404 balun and was monitored. An attenuator pad of approximately 3dB was used at each output of the TRF0213SEP-EVM (J10, J12) and to the balun inputs.

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 SGS100A was controlled via the GPIB bus, using the stand alone LabView™ drivers. The MSO58B was controlled using the 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 TRF0213-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. A thermal imaging camera was employed to verify that the die temperature had stabilized at 125°C before proceeding with measurements

Table 6-1. Equipment Setup and Parameters Used for SEE Testing the TRF0213-SEP

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
VDD (J101)	NI PXIe-4139	3A	3A	5V, 5.25V, 5.5V
INP (J11)	R&S SGS100A	5KHz-6GHz	—	500MHz
OUTP (J10) and OUTM (J12)	Tektronix MSO58B	12bit, 25GS/S	—	25 GS/s

All boards used for SEE testing were fully checked for functionality and dry runs performed to verify 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 TRF0213-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).

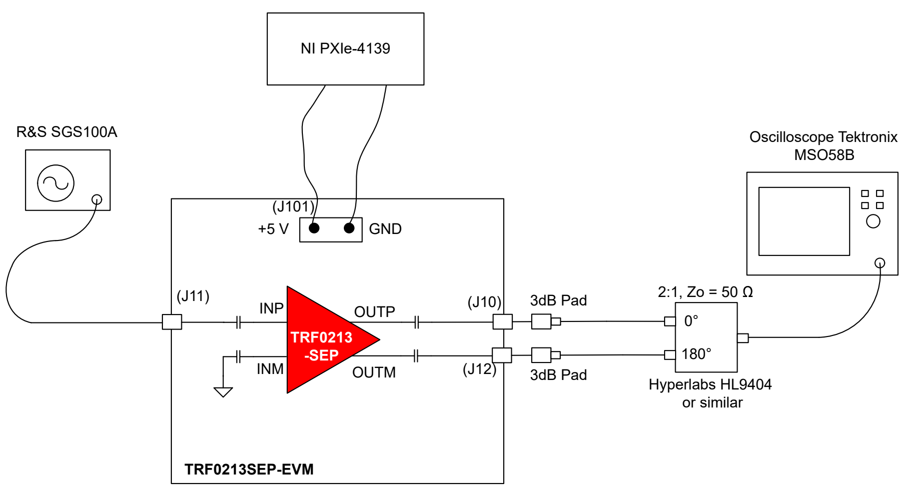

Figure 6-1. Block Diagram of the Test Setup Used for the TRF0213-SEP Mounted on a TRF0213SEP-EVM SEE Characterization

7 Single-Event Latch-up (SEL) Results

During SEL characterization, the device was heated using a closed-loop PID controlled heat gun [MISTRAL 6 System (120V, 2400W)] to 125°C. The temperature of the die was constantly monitored during the testing at TAMU through an IR camera integrated into the control loop to create closed-loop temperature control. The DUT temperature was monitored prior to being irradiated with a FLIR IR-camera to maintain the die-exposed temperature, and hence the junction temperature as shown in Table 7-1. The devices were exposed to a Silver (Ag) heavy-ion beam with normal incidence (0° angle) to the die surface, 40mm airgap, providing an effective Linear Energy Transfer (LET) of 56.1 MeV-cm²/mg. The irradiation was conducted at a flux rate of 1×10^5 ions/cm²·s with fluences of 1×10^7 ions/cm² and 2×10^7 ions/cm² per test run.

The majority of test runs were performed with the device powered at the maximum recommended supply voltage of +5.25V, while a subset of runs utilized the absolute maximum supply voltage of +5.5V. Throughout all irradiation runs, each device actively amplified a single-ended input signal at 500MHz. The quiescent current on the VDD supply pin was continuously monitored and recorded during testing, while the device output was simultaneously monitored using an oscilloscope. A total of three devices underwent SEL testing.

Time duration to achieve this fluence was approximately 2 minutes. No SEL events were observed under any of the test runs, indicating that the TRF0213-SEP is SEL-immune at a die-exposed temperature of T = 125°C and LET = 56.1MeV-cm^2/mg. A supply current vs time plot is shown on Figure 7-1.

Table 7-1. Summary of TRF0213-SEP SEL Results

Run #	Unit #	Die-Exposed Temp. (°C)	Ion Type	Incident Angle (°)	Fluence (× 10^6 ions/cm^2)	Average Flux (× 10^4 ions-cm²/mg)	V_{DD} (V)	Actual LET_{EFF} (MeV-cm²/mg)	Uniformity (%)	Input Power (dBm) at 500MHz	Diff. Output Load (Ω)	Approx V_{OUT} on Scope (mV_{PP})	SEL Result
1	1	125	Ag (107)	0	19.90	11.80	5.25	56.1	92	-10	100	500	Pass
2	1	125	Ag (107)	0	20.00	8.86	5.25	56.1	94	-10	100	500	Pass
3	1	125	Ag (107)	0	20.00	9.94	5.5	56.1	94	10	100	1300	Pass
4	1	125	Ag (107)	0	9.95	9.98	5.25	56.1	94	20	100	1400	Pass
5	2	125	Ag (107)	0	9.95	9.89	5.25	56.1	94	-10	100	500	Pass
6	2	125	Ag (107)	0	9.95	10.20	5.25	56.1	94	10	100	1300	Pass
7	2	125	Ag (107)	0	20.00	10.40	5.5	56.1	94	20	100	1400	Pass
8	2	125	Ag (107)	0	20.00	10.80	5.25	56.1	93	20	100	1400	Pass
9	3	125	Ag (107)	0	9.98	10.70	5.25	56.1	91	-10	100	500	Pass
10	3	125	Ag (107)	0	10.00	10.50	5.5	56.1	92	0	100	1300	Pass
11	3	125	Ag (107)	0	20.00	11.20	5.5	56.1	94	20	100	1400	Pass
12	3	125	Ag (107)	0	20.00	11.20	5.25	56.1	95	-10	100	500	Pass

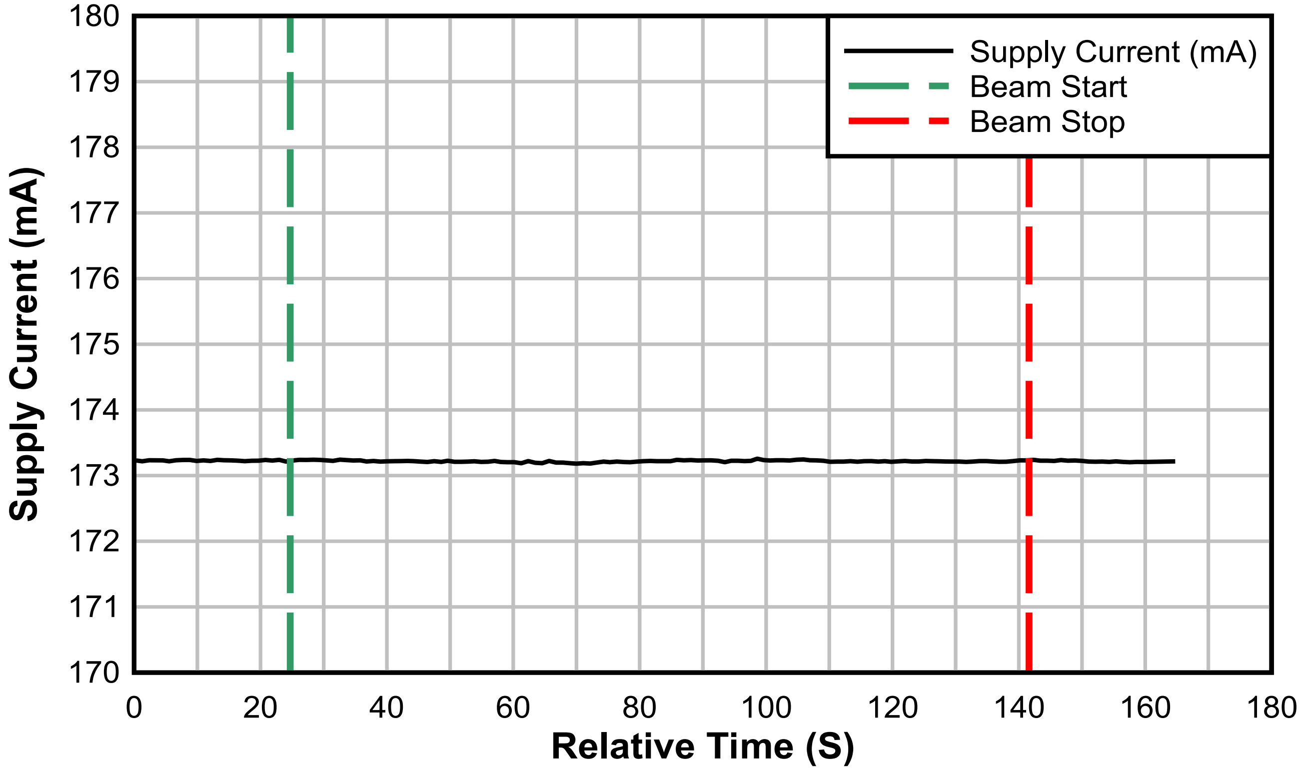

Figure 7-1. Supply Current versus Time Data for SEL Run #4 for the TRF0213-SEP

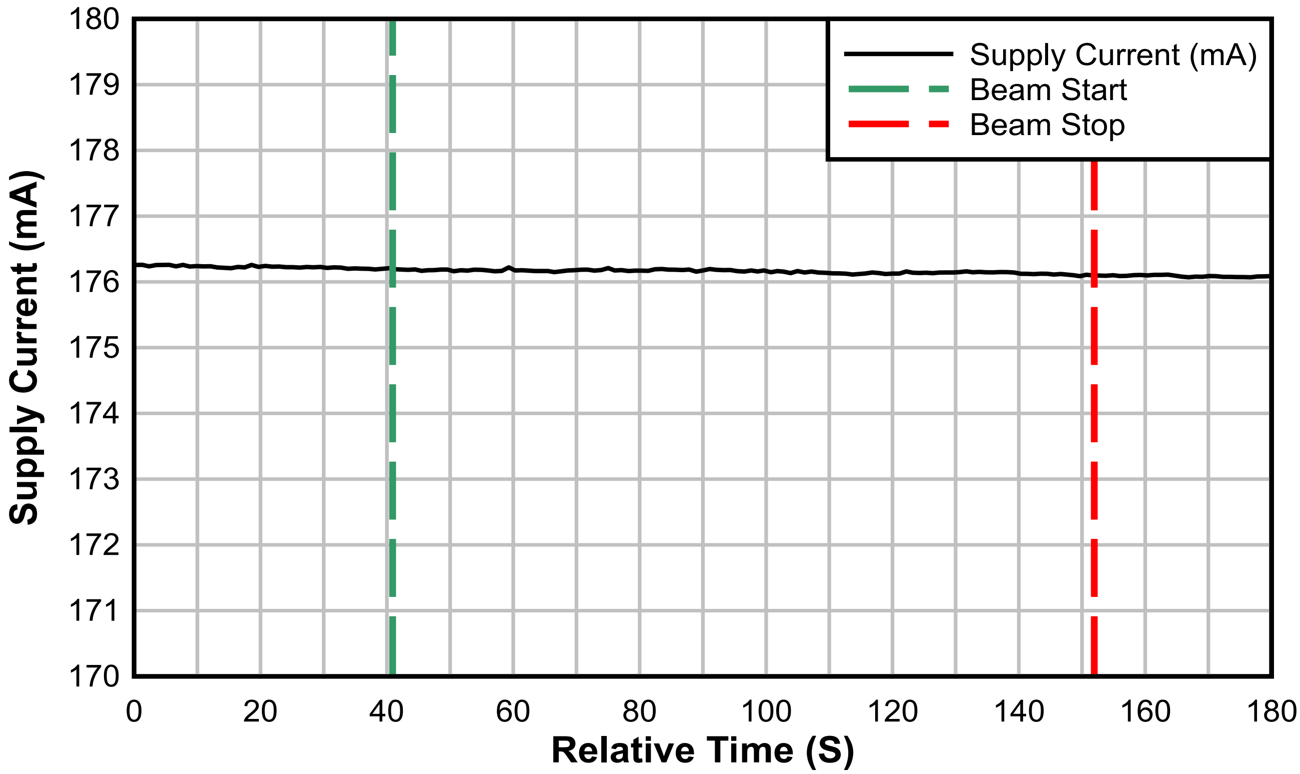

Figure 7-2. Supply Current versus Time Data for SEL Run #5 for the TRF0213-SEP

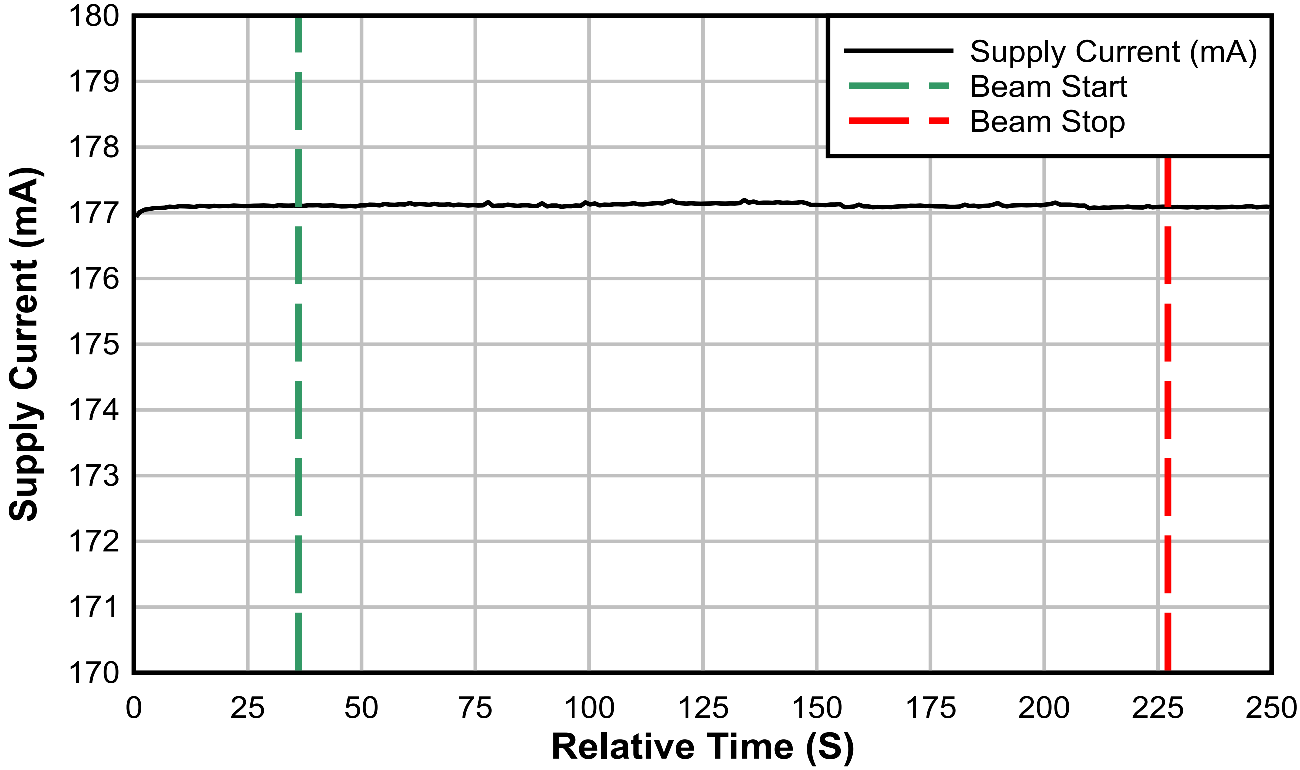

Figure 7-3. Supply Current versus Time Data for SEL Run #11 for the TRF0213-SEP

8 Single-Event Transients (SET) Results

The TRF0213-SEP was characterized for SETs from 1.42 to 56.1MeV-cm^2/mg (refer to Table 5-1) at +5V, +5.5V supply voltages. The device was tested at room temperature for all SETs runs. Since the TRF0213-SEP is a flip chip device, the devices were thinned to 50µm for proper heavy-ion penetration into the active circuits. Flux of 10^4 (most used) ions/cm^2-s and fluence of 2 x 10^6 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 in this report were defined as output voltages excursion that exceed a window trigger set on the MSO58B. Outputs of the TRF0213-SEP were converted to SE using HL9404 balun and monitored. Test conditions used during the testing are presented in Table 8-1. Weibull-Fit and cross section for Unit #4 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 *Single-Event Effects Confidence Interval Calculations*) at 95% confidence interval. The $\sigma_{PERCASE}$ (each row is a case) cross section presented in Table 8-1, was calculated using the MTBF method at 95% confidence. For the SET test, upsets were observed when setting the window trigger to ±20mV and monitoring the output of the balun. Worst case AC upset 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. It was observed that all events recovered in less than 200ns throughout the testing period.

The upper-bound SET cross-sections (σ_{ALL}) was calculated using the events and fluences. Cross-section points for each case are plotted in Figure 8-1 while the Weibull curve fit is generated only using V_{DD} = 5V cases. Using the MTBF method at 95% confidence interval (see *Single-Event Effects Confidence Interval Calculations* for a discussion of the MTBF cross section calculation method), the combined upper bound cross section is:

$\sigma_{SET\text{-}ALL\text{-}AC\text{-}DIFF} \leq 8 \times 10^{-5}$cm^2/device at LET = 56.1MeV-cm^2/mg, T = 25°C, 95% conf. and V_{DD} = +5V, +5.5V

Table 8-1. Summary of the TRF0213-SEP AC Tests at 25°C Exposed Die Temperature(1)

Run #(2)	Unit #	V_{DD} (V)	Ion Type	LET_{EFF} (MeV-cm²/mg)	Average Flux (× 10^3 ions-cm²/mg)	Fluence (× 10^6 # of ions)	Uniformity	#Events (UL = +20mV; LL = –20mV)	Cross Section (× 10^{-6} cm^2)(3)
24	4	5	Ag(109)	56.1	10.30	1.99	95	98	49.2
25	4	5	Ag(109)	56.1	9.97	2.00	95	112	56.0
26	4	5.5	Ag(109)	56.1	9.87	2.01	94	104	51.7
27	4	5.5	Kr(84)	35.2	9.79	2.00	95	52	26.0
28	4	5	Kr(84)	35.2	9.88	2.00	94	49	24.5
29	4	5	Kr(84)	35.2	9.85	2.00	94	50	25.0
30	4	5	Cu(63)	24	10.20	2.00	92	30	15.0
31	4	5	Cu(63)	24	9.90	2.00	92	32	16.0
32	4	5.5	Cu(63)	24	9.21	2.00	95	34	17.0
33	4	5	Ar(40)	9.62	11.40	2.00	98	26	13.0
34	4	5	Ar(40)	9.62	11.40	2.00	98	25	12.5
35	4	5.5	Ar(40)	9.62	11.10	2.00	98	29	14.5
36	4	5	Ne(20)	3.01	17.10	2.00	96	10	5.0
37	4	5	Ne(20)	3.01	9.43	2.00	97	12	6.0
38	4	5.5	Ne(20)	3.01	9.22	2.00	96	11	5.5
42	4	5	N(14)	1.42	9.76	2.00	98	0	0.0
43	4	5	N(14)	1.42	9.96	2.00	99	0	0.0
44	4	5.5	N(14)	1.42	9.93	2.00	99	0	0.0

(1) All SET tests performed at input power = –10dBm.
(2) The run order shown here is not necessarily the order used during heavy-ion characterization of the TRF0213-SEP. Run order was changed for easier appreciation of the results.
(3) Only values corresponding to V_{DD} = 5V are used to generate the Weibull-fit in Figure 8-1.

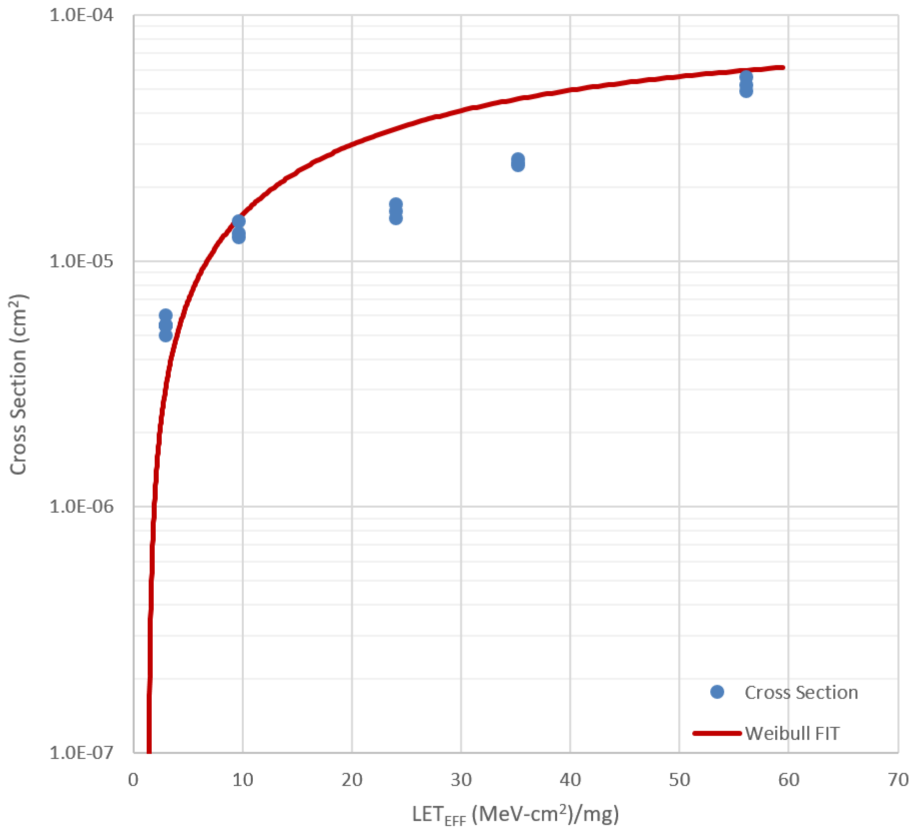

Figure 8-1. Cross Section and Weibull-Fit for DUT #4

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

Table 8-2. Weibull-FIT Parameters for SET, AC Test at Supply Voltage of +5V

Parameter	Value
Onset (MeV-cm^2/mg)	1.42
σ_{SAT} (cm^2)	80 × 10^{-6}
W	40
s	1

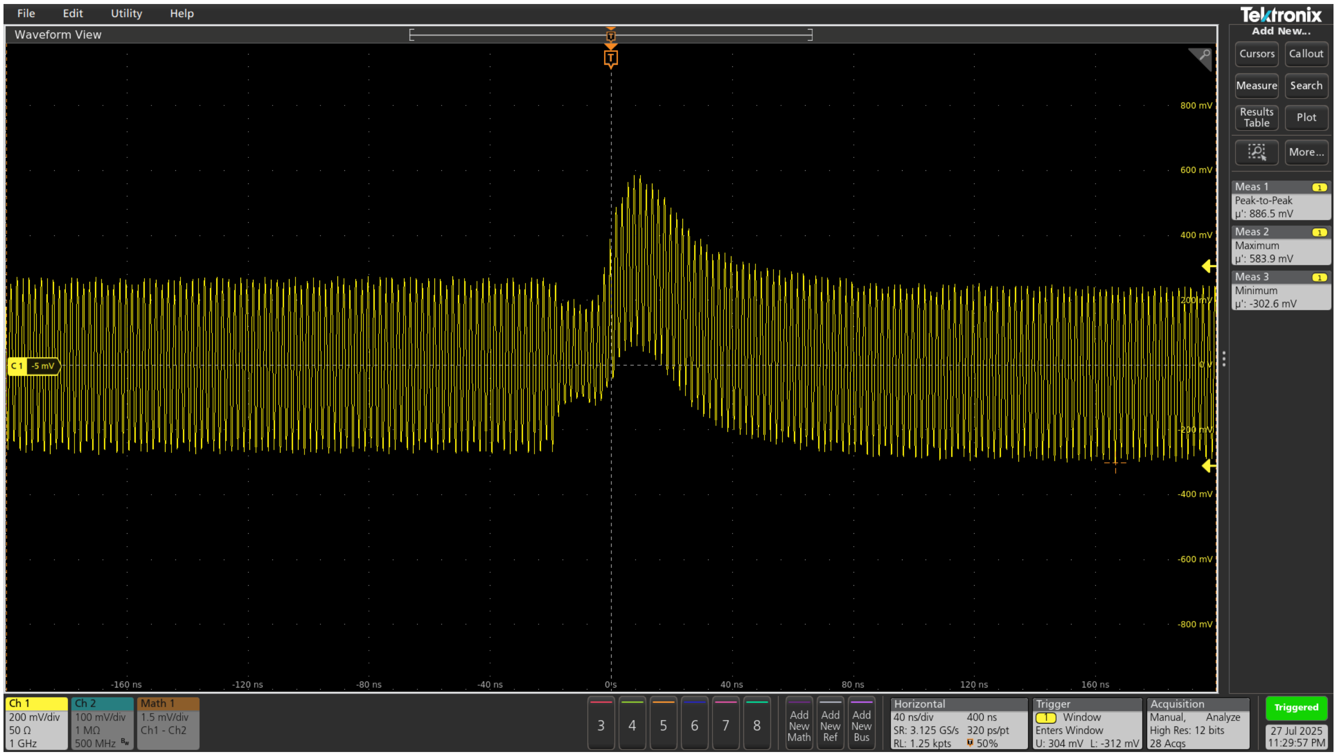

Figure 8-2. Worst Case Upset in AC Test When Monitoring Differential Output of the TRF0213-SEP

9 Summary

The purpose of this study was to characterize the effect of heavy-ion irradiation on the single-event effect (SEE) performance of the TRF0213-SEP, near-DC to > 14GHz, single-ended-to-differential RF amplifier. Extensive SEE testing with heavy-ions having LET_{EFF} from 1.42 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 several supply voltages and input conditions. The SEE results demonstrated that the TRF0213-SEP is SEL-free up to LET_{EFF} = 56.1MeV-cm^2/mg.

A Total Ionizing Dose from SEE Experiments

The production TRF0213-SEP POL is rated to a total ionizing dose (TID) of 30krad(Si), with information-only data provided up to 50krad(Si). In the course of the SEE testing, the heavy-ion exposures delivered ≈ 1krad(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 50krad(Si). The three production TRF0213-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.

11 References

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