Radiation Report

TRF0108-SEP Single-Event Effects (SEE) Radiation Report

ABSTRACT

This report presents the single-event effects performance of the radiation-tolerant TRF0108-SEP following heavy-ion irradiation. Four production devices were irradiated with heavy ions having an effective linear energy transfer (LET_{EFF}) of up to 56.1MeV-cm^2/mg. Single-event latch-up (SEL) testing was conducted on three devices, while single-event transient (SET) characterization was performed on one device. The characterization employed ion fluxes up to 10^5 ions/cm^2-s and fluences up to 10^7 ions/cm^2 at operating temperatures of 25°C for SET testing and 125°C for SEL testing. The results show that the TRF0108-SEP exhibits no single-event latch-up at LET_{EFF} values up to 56.1MeV-cm^2/mg and temperatures up to 125°C. Additionally, the single-event transient cross section is analyzed and discussed.

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1 Overview

The TRF0108-SEP is a very high-performance, differential to single-ended (D2S) amplifier optimized for radio frequency (RF) applications. The device is an excellent choice for applications that require a D2S conversion at the output of digital-to-analog converter (DAC), such as the high-performance DAC39RF10-SEP or AFE7950-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 using Texas Instruments' advanced complementary BICMOS process and is available in a space-saving, WQFN-FCRLF 2mm × 2mm 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 click *here*.

Table 1-1. Overview Information

Description	Device Information
TI Part Number	TRF0108-SEP
Device Function	Differential to Single-Ended Amplifier
Technology	BiCMOS
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Heavy-Ion Fluence per Run	1×10^7 , 2×10^7 ions/cm^2 (SEL) and 2×10^6 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 TRF0108-SEP is resilience against destructive single-event effects (DSEE), such as single-event latch-up (SEL) and single-event burnout (SEB). Since the operating voltage of TRF0108-SEP is relatively low, 5V, SEB is not a concern.

The TRF0108-SEP was characterized for SEL events. In mixed technologies, such as the BiCMOS process used for the TRF0108-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) [7] [6]. 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 TRF0108-SEP exhibited no SEL with heavy-ions of up to LET_{EFF} = 56.1MeV-cm^2/mg at fluences in excess of 10^7 ions/cm^2 and a die temperature of 125°C.

Another concern for high reliability and performance applications is the single-event transient (SET) characteristic of the device. The TRF0108-SEP SET performance was characterized up to LET_{EFF} = 56.1MeV-cm^2/mg. The device was characterized for SET at +5V supply voltage under AC input conditions. Test conditions and results are discussed in Section 8.

3 Test Device and Evaluation Board Information

The TRF0108-SEP is packaged in a 12-pin RPV, WQFN - Flip-Chip RLF (WQFN-FCRLF, 12) package as shown in Figure 3-1. The TRF0108SEP-EVM evaluation board (EVM) was used to evaluate the single-event effects (SEE) of the TRF0108-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. Click *here* for more technical information about the TRF0108-SEP.

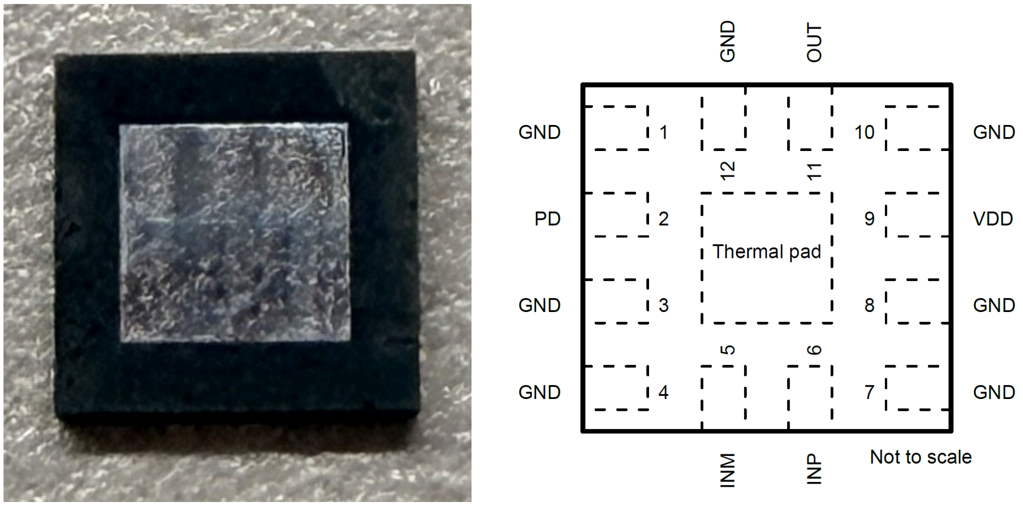


Figure 3-1. Decapped and Background TRF0108-SEP (Left) and Device Pin Out (Right)

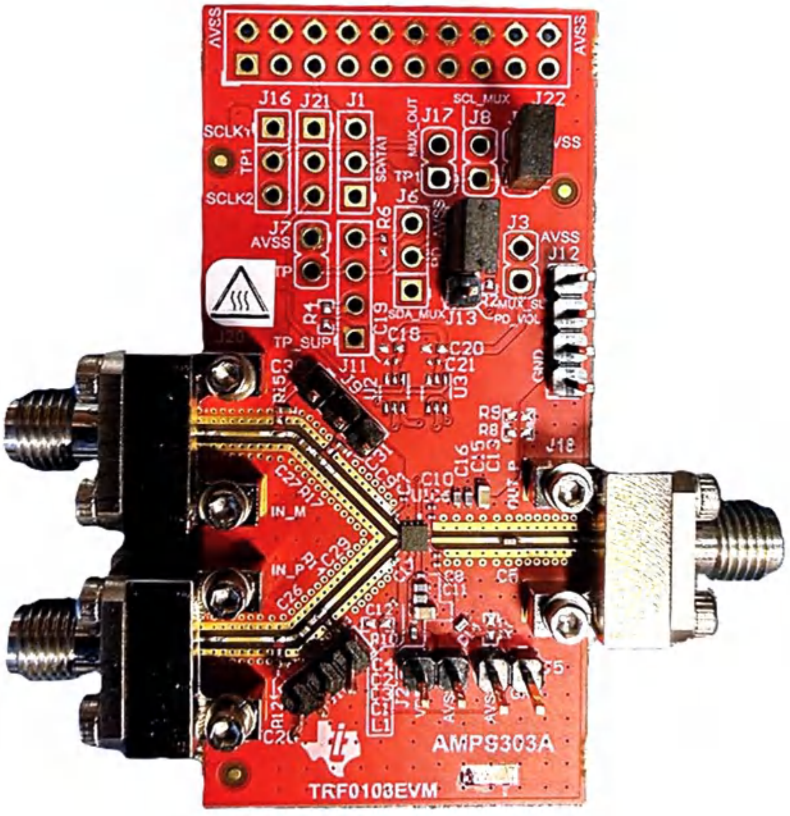


Figure 3-2. TRF0108SEP-EVM Board Top View

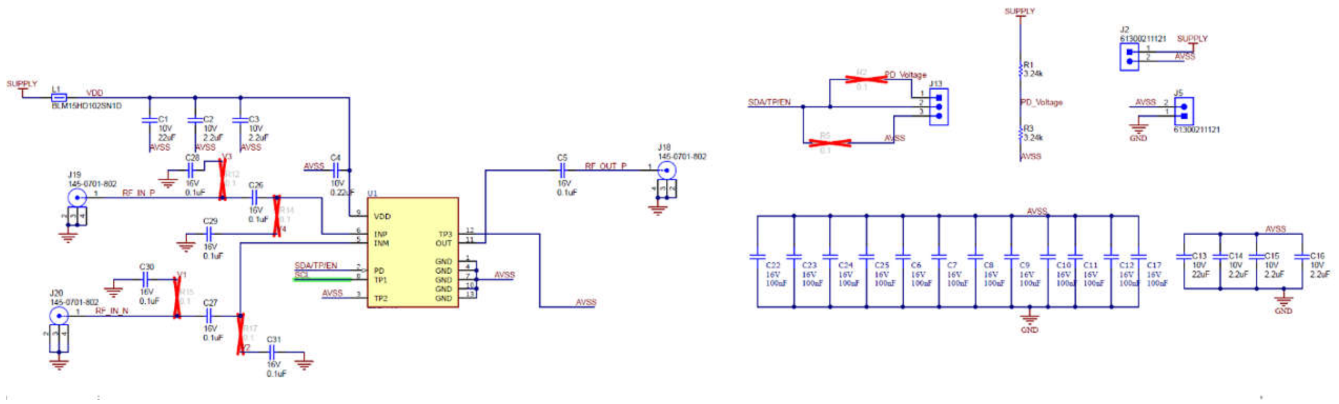


Figure 3-3. TRF0108SEP-EVM, Evaluation Module Board Schematic for SEE Testing

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 K500 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 Nitrogen (^{14}N), Argon (^{40}Ar), Copper (^{63}Cu), Krypton (^{84}Kr), and Silver (^{107}Ag) were used. Angles were used to increment the effective linear energy transfer (LET_{EFF}), details of which are provided in Section 5. Ion beam uniformity for all tests was in the range of 88% to 97%.

Figure 4-1 shows the TRF0108-SEP mounted on the TRF0108SEP-EVM board in front of the beam exit port, as in the heavy-ion characterization. The beam port allows for 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.

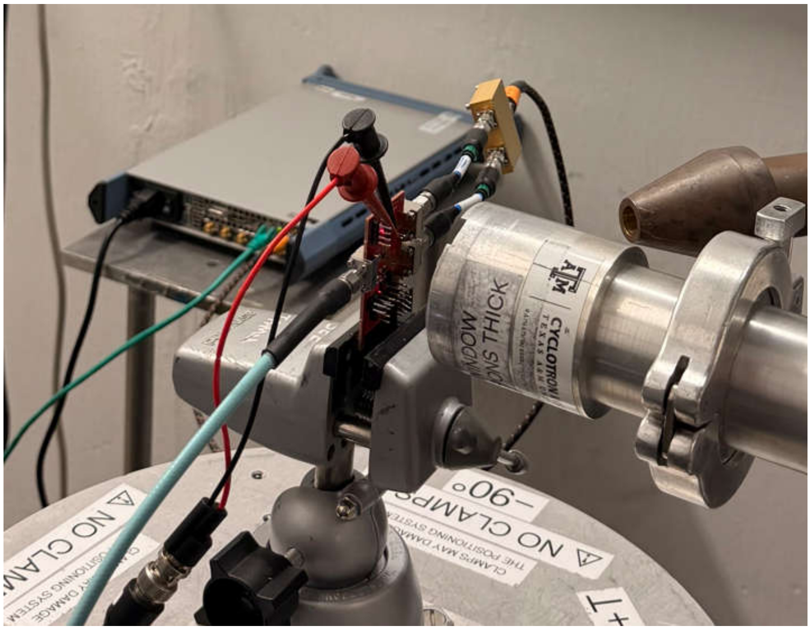
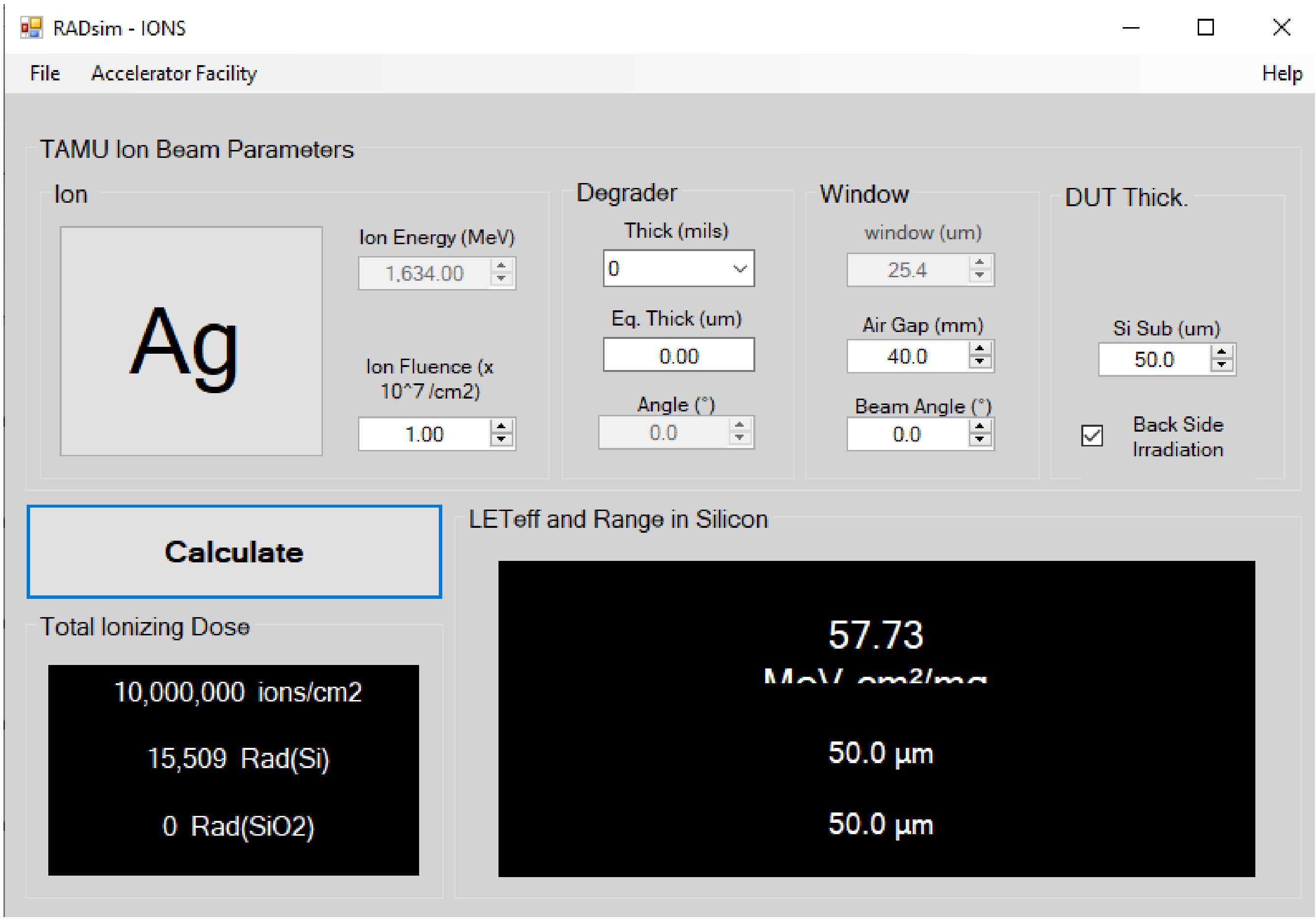


Figure 4-1. Decapped TRF0108-SEP Evaluation Board Mounted in Front of the Heavy-Ion Beam Exit Port

5 Depth, Range, and LET_{EFF} Calculation

TRF0108-SEP is fabricated in TI's 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 [10] models). The application accounts for energy loss in the beam port window setup and the air gap between the DUT and the heavy-ion exit port. An image of the RADsim - IONS is shown in Figure 5-1 and the ions details are presented in Table 5-1. LET_{EFF} values from RADsim - IONS application were used as calculated reference values while the LET_{EFF} values shown in Table 5-1 are based on actual beam logs.



Ion Energy (MeV): 1,634.00
Ion Fluence (x 10^7 /cm2): 1.00
Thick (mils): 0
Eq. Thick (um): 0.00
Angle (°): 0.0
window (um): 25.4
Air Gap (mm): 40.0
Beam Angle (°): 0.0
Si Sub (um): 50.0
☑ Back Side Irradiation

10,000,000 ions/cm2
15,509 Rad(Si)
0 Rad(SiO2)

57.73 MeV cm2/mg
50.0 µm
50.0 µm

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

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	56.1	40

6 Test Set-Up and Procedures

Single-event effects (SEE) testing was conducted on a TRF0108-SEP device mounted on a TRF0108SEP-EVM evaluation board. Power was supplied to the device through the J2 input connector (SUPPLY = +5.25V/+5V and GND) using a PXIe-4139 precision power supply configured in a 4-wire mode. The TRF0108-SEP was evaluated with an ac differential input signal applied to the INP and INM pins, generated by an R&S® SGS100A signal generator (6GHz capability) and converted to differential using a Hyperlabs HL9402 balun connected by high-speed coaxial cables. The input frequency was set to 500MHz. Throughout all testing, the PD pin (J13 jumper) remained connected to ground.

The device was operated in differential mode. Single-event transients (SETs) were monitored using a Tektronix™ MSO58B mixed signal oscilloscope (8channels, 1GHz bandwidth, 25GS/s sampling rate, 62.5M record length). The single-ended output of the SGS100A signal generator was converted to a differential signal using a Hyperlabs HL9402 balun and connected to the differential input of the TRF0108-SEP. The single-ended output of the TRF0108-SEP was connected to the MSO58B oscilloscope configured for 50Ω termination.

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 MSO58B oscilloscope was kept 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. Figure 6-1 shows a block diagram of the setup used for SEE testing of the TRF0108-SEP. Equipment settings and compliance used during the characterization are shown in Table 6-1. For 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

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
VDD (J2)	NI PXIe-4139	3A	3A	5V, 5.25V, 5.5V
INP (J19) and INM (J20)	R&S SGS100A	5kHz-6GHz	—	500MHz
OUT (J18)	Tektronix™ MSO58B	12bit, 25GS/S	—	25GS/s

All boards used for SEE testing were fully checked for functionality and dry runs were 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 TRF0108-SEP device and set the 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).

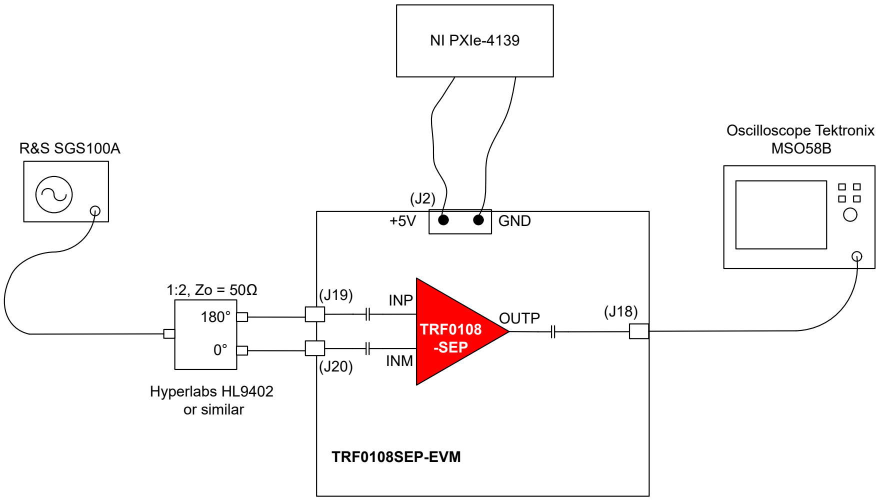


Figure 6-1. Block Diagram of the Test Setup Used for SEE Characterization

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 with a FLIR IR-camera to maintain the die-exposed temperature, and hence the junction temperature as shown in Table 7-1, prior to being irradiated. The devices were exposed to a Silver (Ag) heavy-ion beam with normal incidence (0° angle) to the die surface, and 40mm air gap, providing an effective linear energy transfer (LET_{EFF}) of 56.1MeV-cm^2/mg. The irradiation was conducted at an approximate flux rate of 1×10^5 ions/cm^2-s with fluences of 1×10^7 ions/cm^2 and 2×10^7 ions/cm^2 per test run. The time duration to achieve this amount of fluence was approximately two to three minutes.

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 differential 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.

The SEL results and conditions are summarized in Table 7-1. No SEL events were observed under any of the test runs, indicating that the TRF0108-SEP is SEL-immune at a die-exposed temperature of T = 125°C and LET = 56.1MeV-cm^2/mg. A supply current versus time plot for a few example runs are shown in Figure 7-1 through Figure 7-3.

Table 7-1. Summary of TRF0108-SEP SEL Results

Run #	Unit #	Die-Exposed Temp. (°C)	Ion Type	Incident Angle (°)	Fluence (ions/cm^2)	Average Flux (ions/cm²-s)	V_{DD} (V)	Actual LET_{EFF} (MeV-cm²/mg)	Uniformity (%)	Input Power (dBm) at 500MHz	Approx Output Voltage on Scope (mV_{PP})	SEL Result
1	1	125	Ag (107)	0	2×10^7	1.18×10^5	5.25	56.1	92	–10	500	Pass
2	1	125	Ag (107)	0	2×10^7	0.89×10^5	5.25	56.1	94	–10	500	Pass
3	1	125	Ag (107)	0	2×10^7	0.99×10^5	5.5	56.1	94	10	1300	Pass
4	1	125	Ag (107)	0	1×10^7	1.00×10^5	5.25	56.1	94	20	1400	Pass
5	2	125	Ag (107)	0	1×10^7	0.99×10^5	5.25	56.1	94	–10	500	Pass
6	2	125	Ag (107)	0	1×10^7	1.02×10^5	5.25	56.1	94	10	1300	Pass
7	2	125	Ag (107)	0	2×10^7	1.04×10^5	5.5	56.1	94	20	1400	Pass
8	2	125	Ag (107)	0	2×10^7	1.08×10^5	5.25	56.1	93	20	1400	Pass
9	3	125	Ag (107)	0	1×10^7	1.07×10^5	5.25	56.1	91	–10	500	Pass
10	3	125	Ag (107)	0	1×10^7	1.05×10^5	5.5	56.1	92	0	1300	Pass
11	3	125	Ag (107)	0	2×10^7	1.12×10^5	5.5	56.1	94	20	1400	Pass
12	3	125	Ag (107)	0	2×10^7	1.12×10^5	5.25	56.1	95	–10	500	Pass

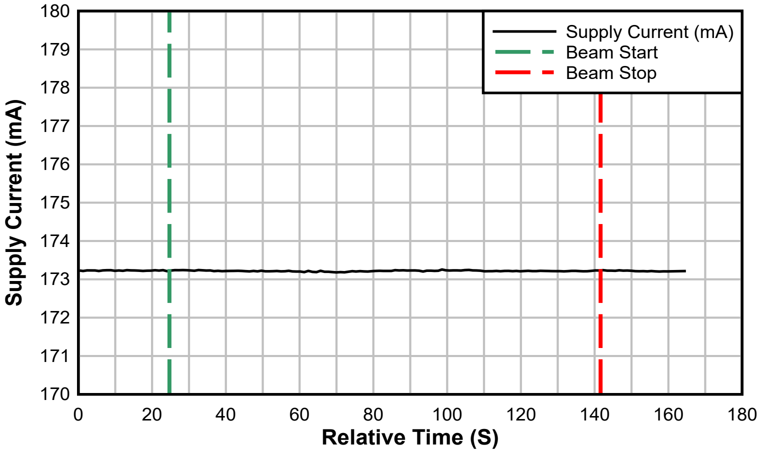


Figure 7-1. Supply Current versus Time Data for SEL Run #4

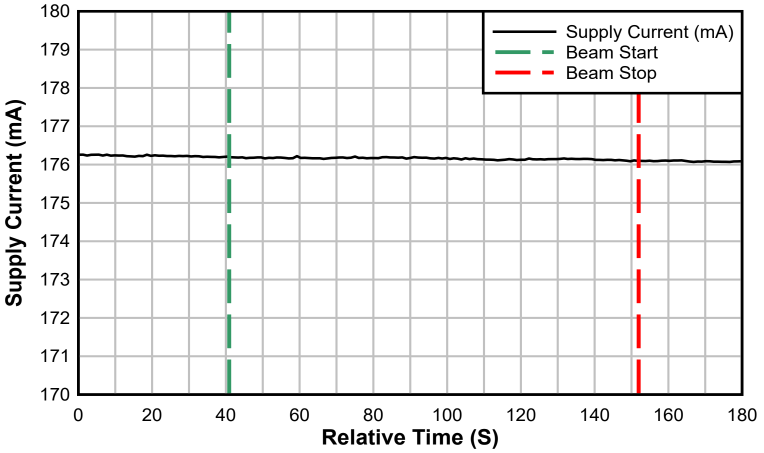


Figure 7-2. Supply Current versus Time Data for SEL Run #5

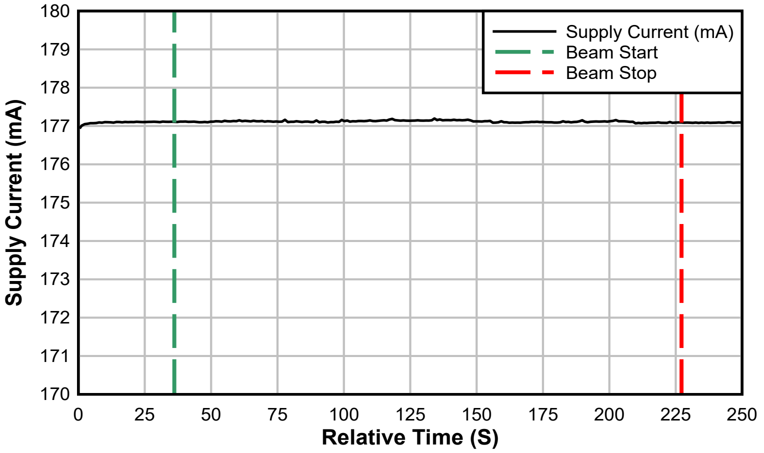


Figure 7-3. Supply Current versus Time Data for SEL Run #11

8 Single-Event Transients (SET) Results

One TRF0108-SEP device was characterized for SETs from 1.42MeV-cm^2/mg to 56.1MeV-cm^2/mg (refer to Table 5-1) at +5V and +5.5V supply voltages. The device was tested at room temperature for all SET runs. Since the TRF0108-SEP is a flip-chip device, the devices were thinned to 50µm for proper heavy-ion penetration into the active circuits. A flux rate of approximately 1×10^4 ions/cm^2-s, and a fluence of approximately 2×10^6 ions/cm^2 per run were used during the heavy-ion characterization. The devices were tested under dynamic (ac) input conditions, as described in Section 6. The SETs discussed in this report were defined as output voltage excursions that exceed a window trigger set on the MSO58B. Output of the TRF0108-SEP device was monitored on the Tektronix™ MSO58B oscilloscope set at 50Ω termination. Test conditions used during the testing are presented in Table 8-1. Weibull-Fit and cross section for Unit #4 are presented in Table 8-1. To calculate the cross section values at different LET_{EFF} levels, the total number of upsets (or transients) and the fluences where combined (added 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 σ_{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 by setting the window trigger to ±300mV and monitoring the output of TRF0108-SEP. Worst case ac upset is shown in Figure 8-2. Though not observed during the testing, note that an SET event can result in the output going up to the saturation voltage. All events recovered in approximately 200ns or less throughout the testing period.

The upper-bound SET cross-sections (σ_{SET}) were calculated using the events and fluences. 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:

$$\sigma_{\text{SET-ALL-RUNs}} \leq 60 \times 10^{-6}\text{cm}^2\text{/device at LET}_{\text{EFF}} = 56.1\text{MeV-cm}^2\text{/mg, T} = 25°\text{C, 95\% conf. and V}_{\text{DD}} = +5\text{V, +5.5V}$$

Table 8-1. Summary of the TRF0108-SEP SET Results at 25°C Exposed Die Temperature(1)

Run #(2)	Unit #	V_{DD} (V)	Ion Type	LET_{EFF} (MeV-cm^2/mg)	Average Flux Rate (× 10^3 ions/cm^2-s)	Fluence (× 10^6 ions/cm^2)	Uniformity	#Events (UL = +300mV; LL = –300mV)	Cross-Section, σ_{SET} (× 10^{-6} cm^2)
24	4	5	Ag(109)	56.1	10.32	1.99	95	98	49.2
25	4	5	Ag(109)	56.1	9.97	2.00	95	112	55.9
26	4	5.5	Ag(109)	56.1	9.87	2.01	94	104	51.9
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	10.18	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	11.37	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	17.05	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 with device output voltage swing set such that the reported swing on the oscilloscope was approximately $\pm 150\text{mV}_{\text{PP}}$.
(2) The run order shown here is not necessarily the order used during heavy-ion characterization of the TRF0108-SEP. Run order was changed for easier appreciation of the results.

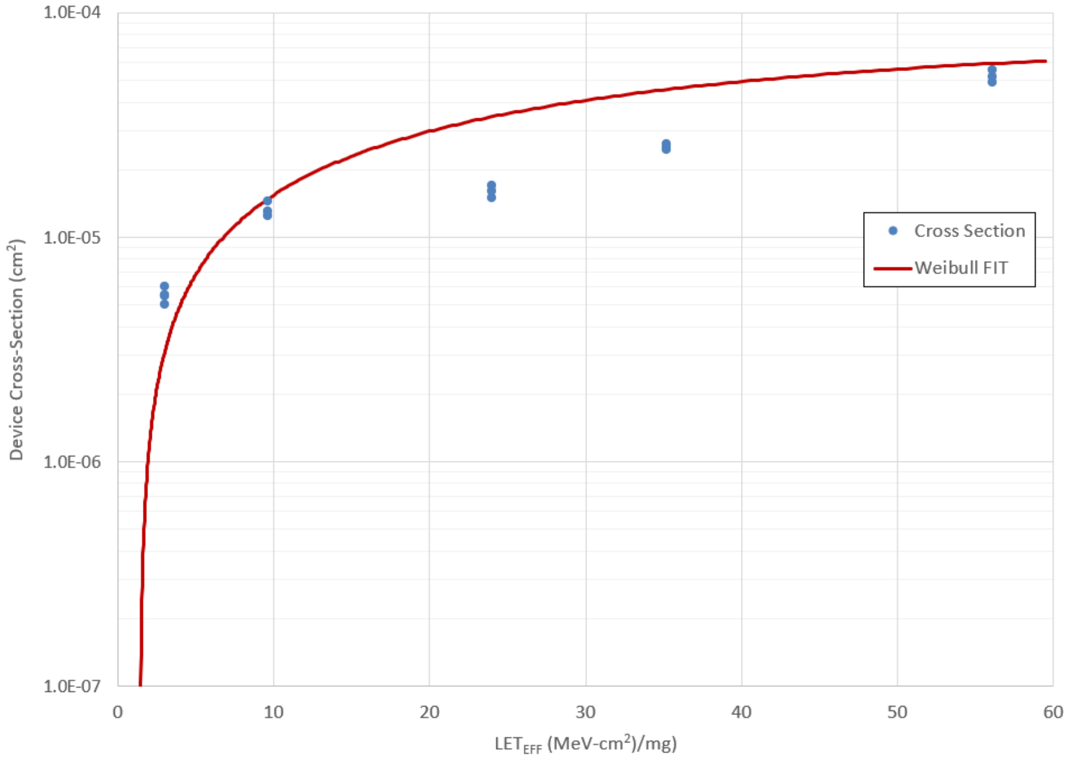
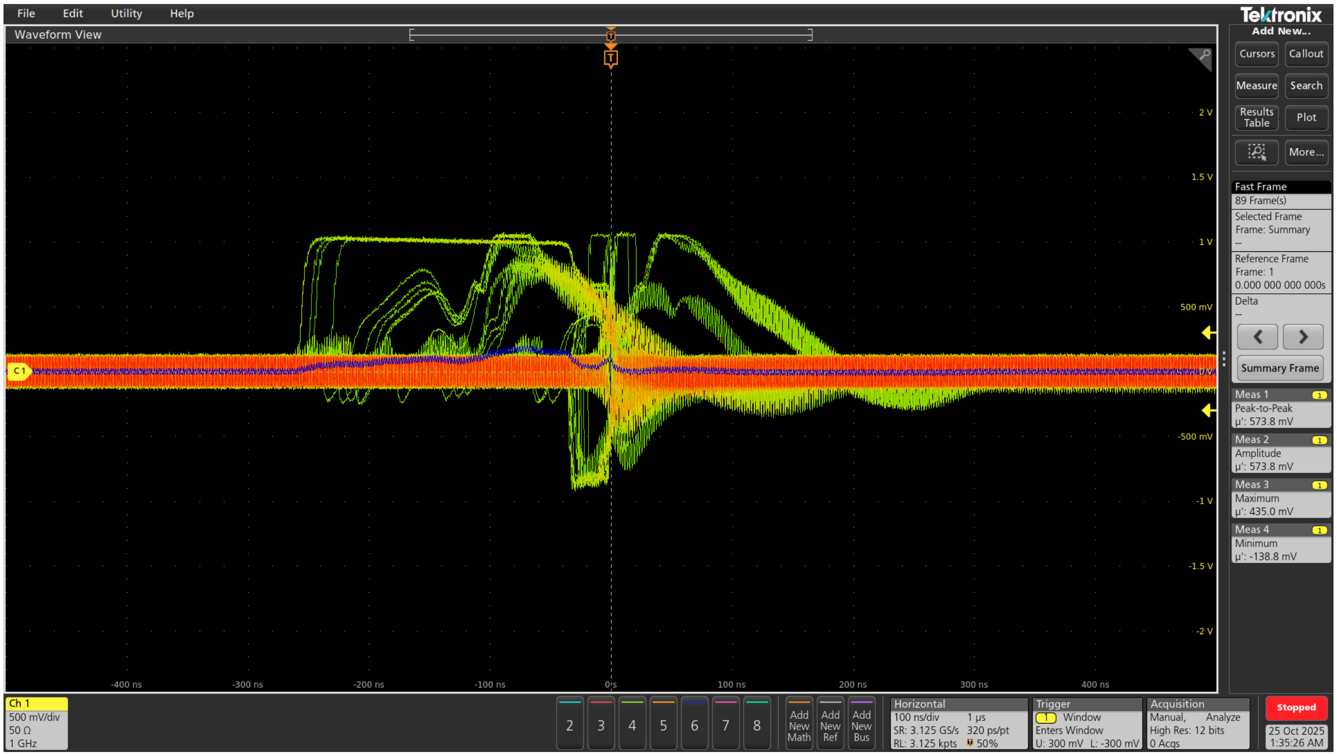


Figure 8-1. Cross-Section and Weibull-Fit for Unit #4

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

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

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



Fast Frame
89 Frame(s)
Selected Frame
Frame: Summary
--
Reference Frame
Frame: 1
0.000 000 000 000s
Delta
--

Meas 1
Peak-to-Peak
μ': 573.8 mV

Meas 2
Amplitude
μ': 573.8 mV

Meas 3
Maximum
μ': 435.0 mV

Meas 4
Minimum
μ': -138.8 mV

Ch 1
500 mV/div
50 Ω
1 GHz

Horizontal
100 ns/div 1 μs
SR: 3.125 GS/s 320 ps/pt
RL: 3.125 kpts 50%

Trigger
1 Window
Enters Window
U: 300 mV L: -300 mV

Acquisition
Manual, Analyze
High Res: 12 bits
0 Acqs

25 Oct 2025
1:35:26 AM

Figure 8-2. All Transients Overlaid in SET Test When Monitoring Output of the TRF0108-SEP for Run #38 (LET_{EFF} = 56.1 MeV-cm^2/mg)

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 (2.54mm) 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 TRF0108-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-cm^2/mg)	σ_{SAT} (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	1.4200	80×10^{-6}	0.18×10^{-3}	7.37×10^{3}	15.49
GEO			1.52×10^{-3}	63.41×10^{3}	1.80

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 TRF0108-SEP. 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 2×10^6 to 2×10^7 per run, at several supply voltages and input conditions. The SEE results demonstrated that the TRF0108-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 TRF0108-SEP in two harshly conservative space environments.

A Total Ionizing Dose from SEE Experiments

The production TRF0108-SEP is rated to a total ionizing dose (TID) of 30krad(Si), with 50krad(Si) as information-only data. In the course of the SEE testing, the heavy-ion exposures delivered approximately 1krad(Si) per 10^6 ions/cm^2 run. The cumulative TID exposure for each device respectively, over all runs each underwent, was determined to be greater than 30krad(Si). The production TRF0108-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.

12 References

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