Radiation Report

TPS7H2221-SEP Single-Event Effects (SEE) Test Report

TEXAS INSTRUMENTS

ABSTRACT

The purpose of this study is to characterize the single-event-effects (SEE) performance due to heavy-ion irradiation of the TPS7H2221-SEP. SEE performance was verified at an input voltage range of 1.6-V to 5.5-V. Heavy-ions with LET_{EFF} of 42.7 and 46.8 MeV·cm^2/mg were used to irradiate 6 production devices. Flux of ≈10^5 ions/cm^2·s and fluences of ≈10^7 ions/cm^2 per run were used for the DSEE characterization and flux of ≈10^4 or 10^5 ions/cm^2·s and fluences of ≈3 x 10^6 or 10^7 for the SET testing. The results demonstrated that the TPS7H2221-SEP is single-event latch-up (SEL), single-event burnout (SEB), and single-event gate rupture (SEGR) -free up to 46.8 MeV·cm^2/mg, at T = 125°C and T = 25°C, respectively, and across the full electrical specifications. Single event transient (SET) performance for output voltage excursions ≥ |3%| from the nominal voltage are discussed.

Table of Contents

List of Figures

List of Tables

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1 Introduction

The TPS7H2221-SEP is a space-enhanced-plastic, 1.6-V to 5.5-V input, 1.25-A, load switch with a controlled slew rate. A controllable ON state is controlled by digital input that is capable of interfacing directly with low-voltage control signals.

The device is offered in a SC-70 package characterized for a temperature range of -55°C to 125°C. General device information and test conditions are listed in Table 1-1. For more detailed technical specifications, user-guides, and application notes please go to TPS7H2221-SEP product page.

Table 1-1. Overview Information

DESCRIPTION(1)	DEVICE INFORMATION
TI Part Number	TPS7H2221-SEP
Orderable Number	TPS7H2221MRGWSEP
Device Function	Load Switch
Technology	Linear BiCMOS 9 (LBC9)
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University (15 and 25 MeV/nucleon)
Heavy Ion Fluence per Run	3.00×10^6 and 1×10^7 ions/cm^2
Irradiation Temperature	25°C (for SEB/SEGR and SET testing), and 125°C (for SEL testing)

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2 Single-Event Effects (SEE)

The primary concern for the TPS7H2221-SEP is the robustness against the destructive single-event effects (DSEE): single-event latch-up (SEL), single-event burnout (SEB), and single-event gate rupture (SEGR). In mixed technologies such as the BiCMOS process used on the TPS7H2221-SEP, the CMOS circuitry introduces a potential for SEL susceptibility.

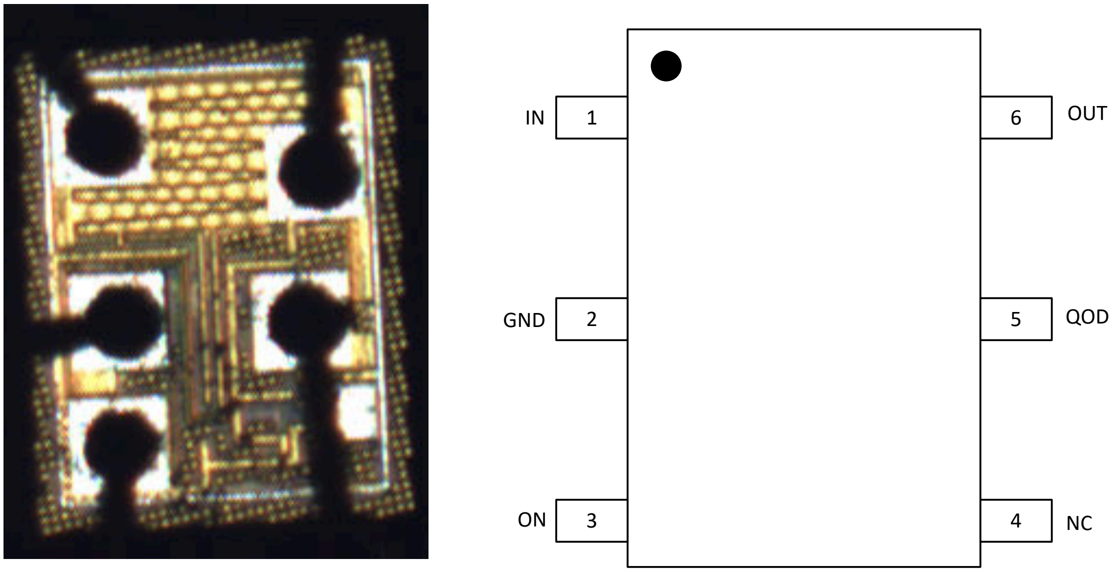
SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-sub and n-well and n+ and p+ contacts) [1,2]. The parasitic bipolar structure initiated by a single-event creates a high-conductance path (inducing a steady-state current that is typically orders-of-magnitude higher than the normal operating current) between power and ground that persists (is “latched”) until power is removed, the device is reset, or until the device is destroyed by the high-current state. The TPS7H2221-SEP was tested for SEL at a maximum recommended input voltage of 5.5-V and a load of 1.25-A. Testing was done with a discrete power resistor of 4.4 Ω or a Chroma E63600 ELoad in Constant Resistance (CR) mode. During the SEL testing a Closed-Loop PID controlled heat gun (MISTRAL 6 System (120V, 2400W)) was used to heat the device to 125°C. A FLIR (FLIR ONE Pro LT) thermal camera was used to validate die temperature to ensure the device was being accurately heated. The device exhibited no SEL with heavy-ions with up to LET_{EFF} = 46.8 MeV·cm^2/mg, flux ≈10^5 ions/cm^2·s and fluences of ≈10^7 ions/cm^2.

The TPS7H2221-SEP was evaluated for SEB/SEGR at a load of 1.25-A and an input voltage of 5.5-V. The device was tested under enabled and disabled modes. During the SEB/SEGR testing, not a single current event was observed, demonstrating that the TPS7H2221-SEP is SEB/SEGR-free up to LET_{EFF} = 46.8 MeV·cm^2/mg at a flux of ≈10^5 ions/cm^2·s, fluences of ≈10^7 ions/cm^2, and a die temperature of ≈25°C.

The TPS7H2221-SEP was characterized for SET at flux of ≈10^4 or 10^5 ions/cm^2·s, fluences of ≈3 x 10^6 or 10^7 ions/cm^2, and a die temperature of about 25°C. The device was characterized at V_{IN} = 1.8-V, 3.3-V, and 5-V with varying loads of 100-mA to 1.25-A. Under these conditions all recorded V_{OUT} voltage excursions self-recover with no external intervention.

3 Device and Test Board Information

The TPS7H2221-SEP is packaged in a DCK 6-pin SC70 plastic package as shown in Figure 3-1. The TPS7H2221 EVM was used to evaluate the performance and characteristics of the TPS7H2221-SEP under heavy-ions. Figure 3-2 shows the top view of the board used for the radiation testing. Figure 3-4 shows the board schematics used for the heavy-ion testing campaign.



Note: Because the device is a flip chip, the package was delidded on the bottom to reveal the die face for all heavy-ion testing.

Figure 3-1. Photograph of Delidded TPS7H2221-SEP [Left] and Pinout Diagram [Right]

Because this device is a flip chip a hole was drilled in the board and SEE testing was done "from the back". The ability to see the exposed die through the hole was validated on all EVMs prior to SEE testing. Since the board is dual-site both units were verified and used for testing while under the beam. The boards used for these experiments were modified from the orderable EVM specifically for the test cases discussed in this report and to allow for full dual-site capabilities. For any testing done with the orderable EVM only the bottom circuit (U2) can be used as drilling a hole at U1 would isolate the GND pin from the board.

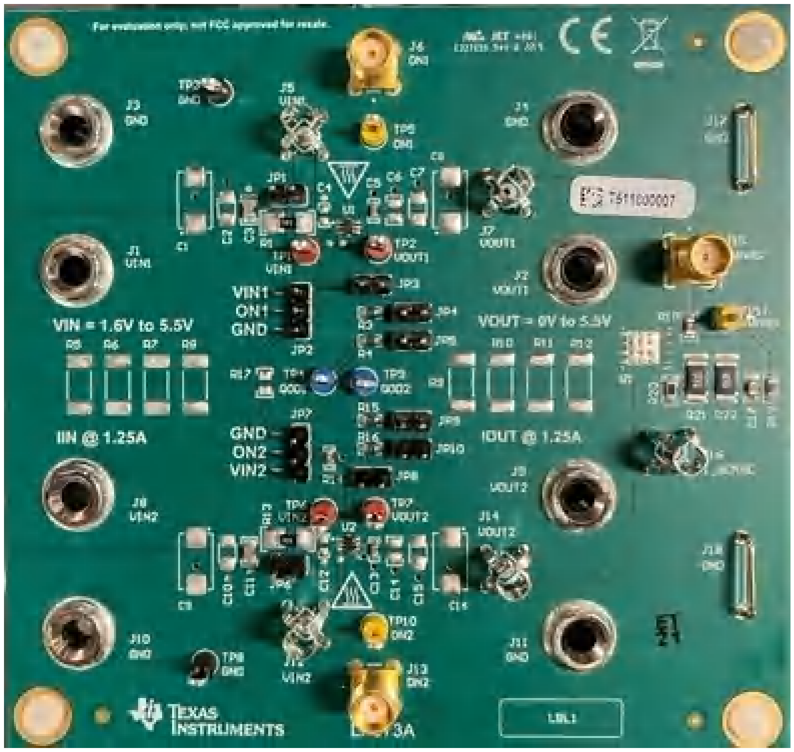


Figure 3-2. TPS7H2221-SEP Board Top View

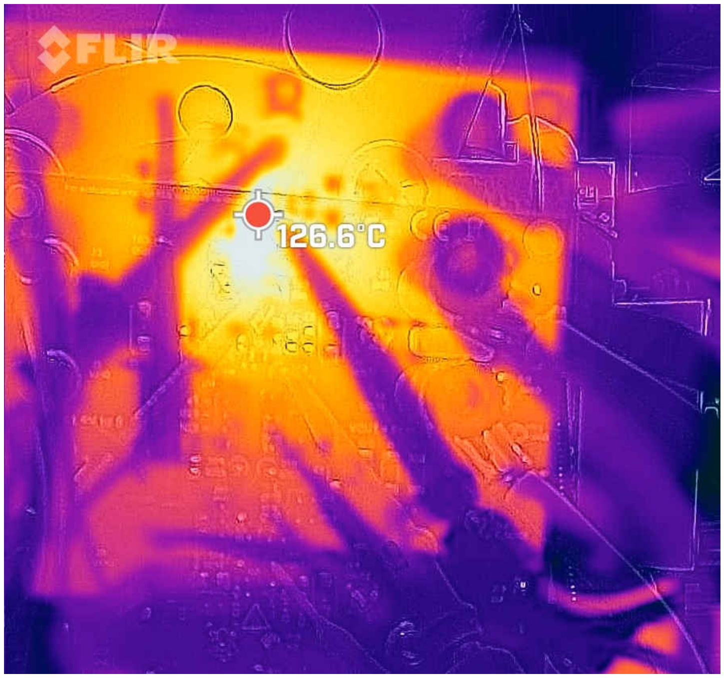


Figure 3-3. TPS7H2221-SEP Thermal Image for SEL

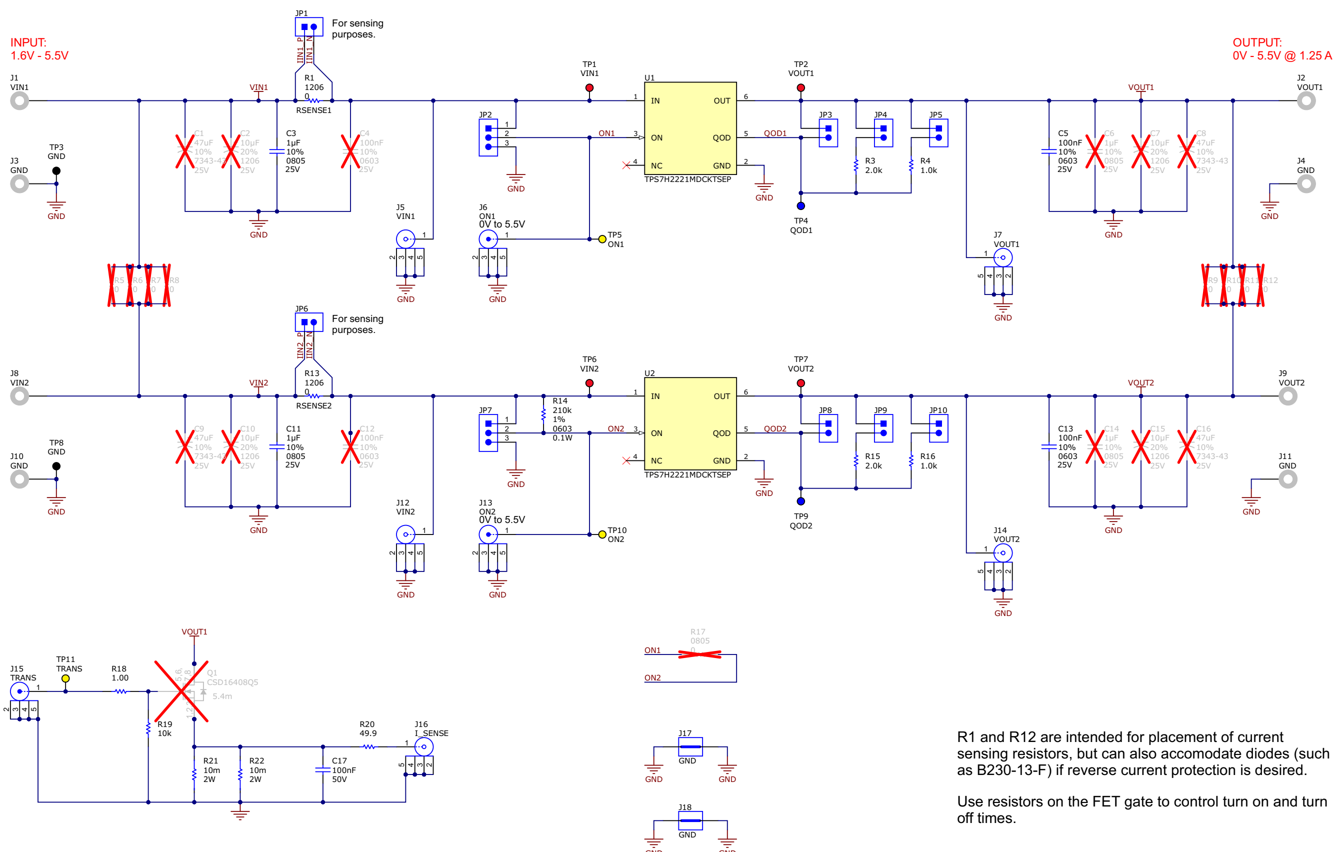


Figure 3-4. TPS7H2221EVM Schematic

4 Irradiation Facility and Setup

The heavy-ion species used for the SEE studies on this product were provided and delivered by the TAMU Cyclotron Radiation Effects Facility using a superconducting cyclotron and an 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 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 flux of 10^4 or 10^5 ions/cm^2·s were used to provide heavy-ion fluences of 3 x 10^6 and 1 x 10^7 ions/cm^2.

For the experiments conducted on this report, ^{129}Xe and ^{109}Ag ions at angle of incidence of 0° for an LET_{EFF} of 42.7 and 46.8 MeV·cm^2/mg respectively were used. The total kinetic energies of ^{129}Xe and ^{109}Ag in the vacuum are 3.197 GeV (25 MeV/nucleon) and 1.634 GeV (15 MeV/nucleon) respectively. Ion uniformity for these experiments was between 89 and 98%.

Figure 4-1 shows the TPS7H2221-SEP test board used for the experiments at the TAMU facility. The beam port has a 1-mil Aramica window to allow in-air testing while maintaining the vacuum within the accelerator with only minor ion energy loss. Because the devie is a flip chip a hole was drilled in the "back" of the board so that the die could be irradiated during testing. The in-air gap between the device and the ion beam port window was maintained at 40 mm for all runs.

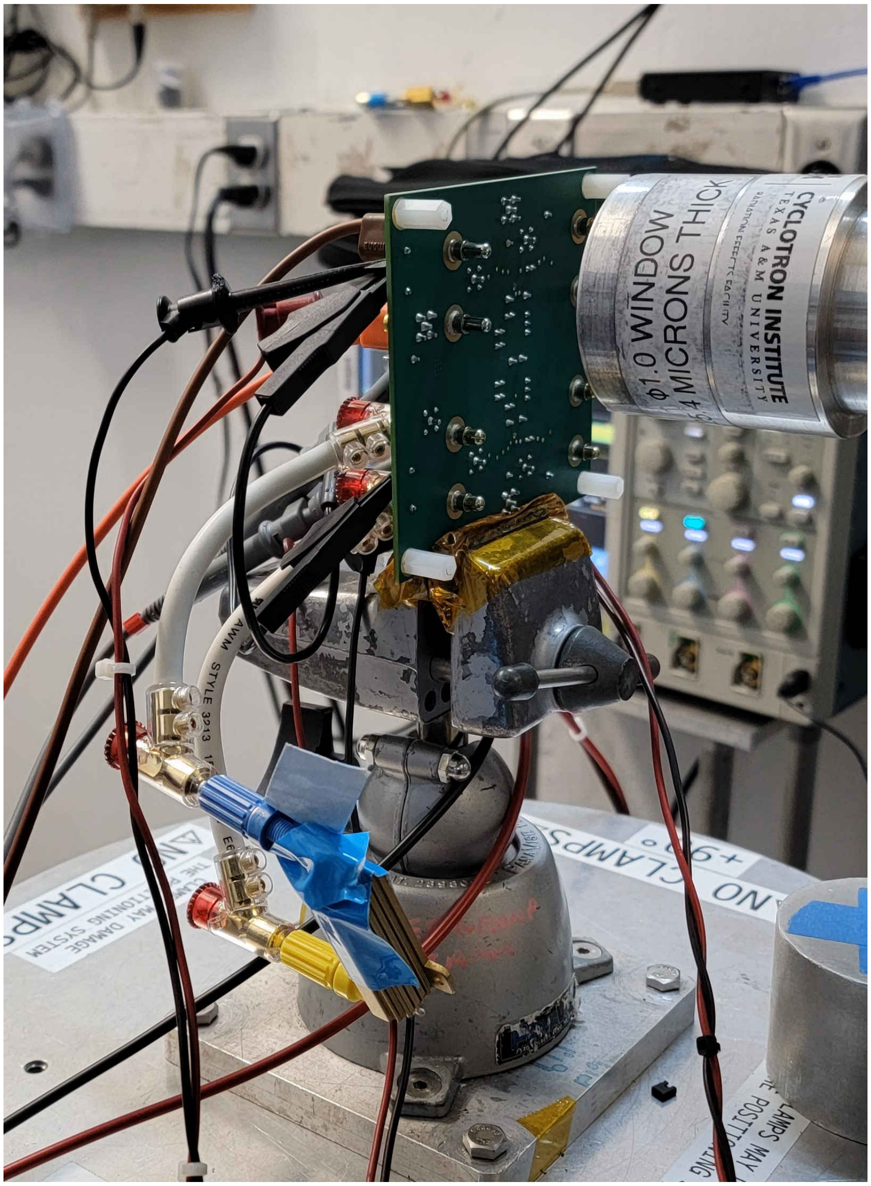


Figure 4-1. Photograph of the TPS7H2221-SEP Evaluation Board at the Texas A&M Cyclotron

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

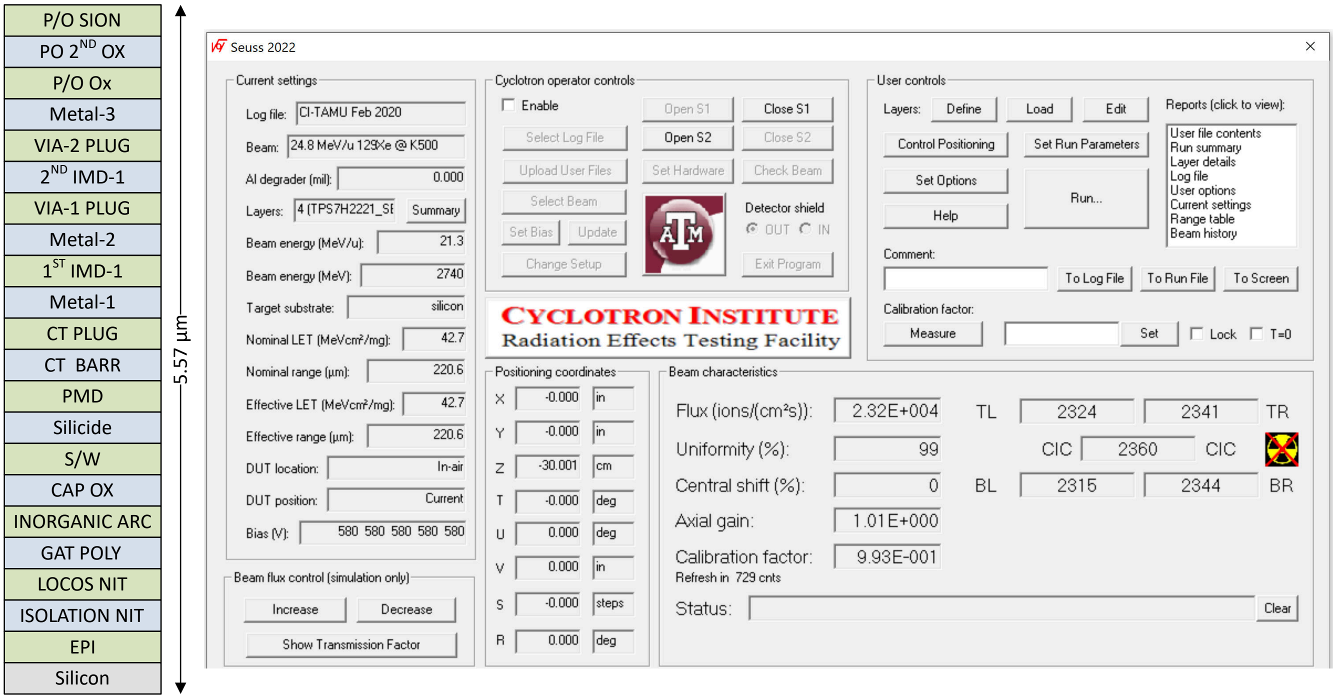


Figure 5-1. Generalized Cross-Section of the LBC9 Technology BEOL Stack on the TPS7H2221-SEP [Left] and SEUSS 2021 Application Used to Determine Key Ion Parameters [Right]

The TPS7H2221-SP is fabricated in the TI LBC9 process with a back-end-of-line (BEOL) stack consisting of 3 levels of standard thickness aluminum metal on a 0.5-µm pitch. The total stack height from the surface of the passivation to the silicon surface is 5.57 µm based on nominal layer thickness as shown in Figure 5-1. Accounting for energy loss through the 1-mil thick Aramica beam port window, the 40-mm air gap, and the BEOL stack over the TPS7H2221-SEP, the effective LET (LET$_{EFF}$) at the surface of the silicon substrate, the depth, and the ion range was determined with the SEUSS 2020 Software (provided by the Texas A&M Cyclotron Institute and based on the latest SRIM-2013 [7] models). The results are shown in Table 5-1. The LET$_{EFF}$ vs range for the heavy-ions used is shown on Figure 5-2. The stack was modeled as a homogeneous layer of silicon dioxide (valid since SiO_2 and aluminum density are similar).

Table 5-1. Xenon Ion LET$_{EFF}$, Depth, and Range in Silicon

ION TYPE	ANGLE OF INCIDENCE	DEGRADER STEPS (#)	DEGRADER ANGLE	RANGE IN SILICON	LET$_{EFF}$ (MeV·cm^2/mg)
^{129}Xe	0	0	0	214.2	42.7
^{109}Ag	0	0	0	99.5	46.8

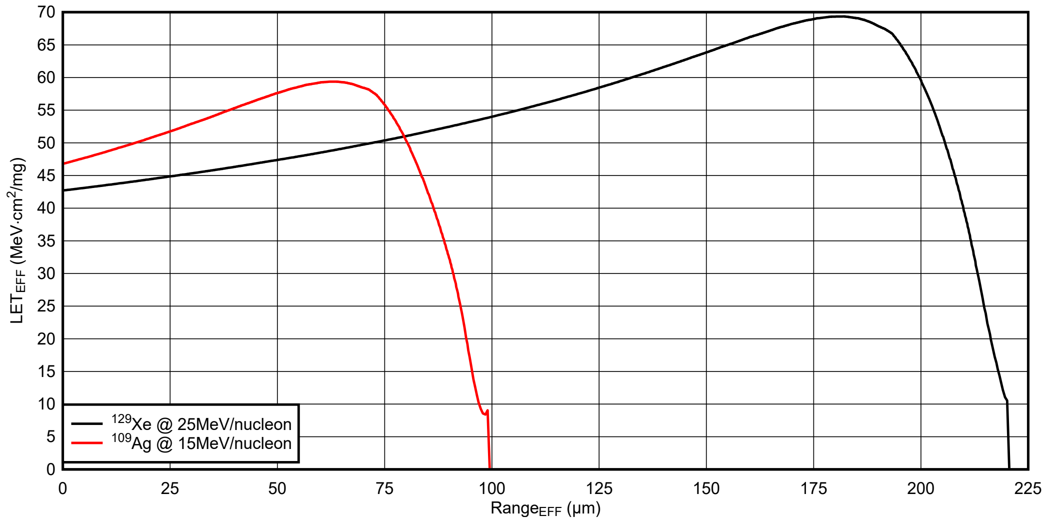


Figure 5-2. LET_{EFF} vs Range for ^{129}Xe and ^{109}Ag at the Conditions Used for the SEE Test Campaign

6 Test Setup and Procedures

SEE testing was performed on a TPS7H2221-SEP device mounted on a two-site (U1 and U2) EVM designed for the device and modified specifically for radiation testing. The device power was provided using the J1 (VIN) and J3 (GND) inputs for U1 and the J8 (VIN) and J10 (GND) for U2 with the N6766A and N6765A PS Module, respectively, mounted on a N6705 precision power supply. A combination of a 4.4 Ω power resistor and a Chroma E-Load in constant resistance (CR) mode was used to load the device using J2 (VOUT) and J4 (GND) for U1 and J9 (VOUT) and J11 (GND) for U2.

For SEL, SEB, and SEGR testing, the device was powered up to an operating voltage of 5.5-V and loaded to 1.25-A with the 4.4 Ω power resistor or the Chroma E-Load.

For the SEB/SEGR characterization, the device was tested under enabled and disabled modes. The device was disabled by using the TP5 and TP10 (ON) pins for U1 and U2, forcing 0 V using a PXIe-4139. The power resistor was connected even when the device was disabled to help differentiate if an SET momentarily activated the device under the heavy-ion irradiation. During the SEB/SEGR testing with the device in disabled mode, not a single V_{OUT} transient or input current event was observed.

For the SET characterization, the device was powered up in the following configurations:

- V_{IN} = 1.8-V, I_{OUT} = 0.1-A
- V_{IN} = 1.8-V, I_{OUT} = 0.5-A
- V_{IN} = 3.3-V, I_{OUT} = 0.1-A
- V_{IN} = 3.3-V, I_{OUT} = 1.25-A
- V_{IN} = 5-V, I_{OUT} = 0.1-A
- V_{IN} = 5-V, I_{OUT} = 1.25-A

The SET events were monitored using a National Instruments™ (NI) PXIe-5172 scope card. The scope was used to monitor and trigger from V_{OUT}, using a window trigger around ±3% from the nominal output voltage. The scope was mounted on a NI PXIe-1095 chassis.

All equipment was controlled and monitored using a custom-developed LabVIEW™ program (PXI-RadTest) running on a HP-Z4™ desktop computer. The computer communicates with the PXI chassis via an MXI controller and NI PXIe-8381 remote control module.

Figure 6-1 shows a block diagram of the setup used for SEE testing of the TPS7H2221-SEP. Table 6-1 shows the connections, limits, and compliance values used during the testing. A die temperature of 125°C was used for SEL. For the SEB/SEGR and SET characterization, the devices were tested at room temperature (no cooling or heating was applied to the DUT). The die temperature was verified using a IR-camera before the exposure to heavy ions.

Table 6-1. Equipment Set and Parameters Used for SEE Testing the TPS7H2221-SEP

For the Chroma E-Load "High Range" in the compliance column refers to the mode that the chroma was in during testing, not necessarily a current compliance.

PIN NAME	EQUIPMENT USED	CAPABILITY	COMPLIANCE	RANGE OF VALUES USED
VIN1	Agilent N6766A PS	17 A	10 A	1.6-V to 5.5-V
VIN2	Agilent N6765A PS	50 A	10 A	1.6-V to 5.5-V
EN1/2	PXIe-4139	3 A	0.1 A	1.6-V to 5-V
Oscilloscope Card on V_{OUT}	NI-PXIe 5172	100 MS/s	—	2.5 MS/s
Chroma E-Load on V_{OUT}	E36300-80-60	80 A	High Range	0.1-A to 1.5-A

All boards used for SEE testing were fully checked for functionality. Dry runs were also 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 TPS7H2221-SEP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability were 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). During irradiation, the NI scope cards continuously monitored the signals. When the output voltage exceeded the pre-defined ±3% window trigger a data capture was initiated. In addition to monitoring the output voltage, VIN current and the +5-V (beam shutter ON/OFF) signal from TAMU were monitored at all times. No sudden increases in current were observed (outside of normal fluctuations) on any of the test runs and indicated that no SEL or SEB/SEGR events occurred during any of the tests.

Although there were two sites on the radiation test board, only 1 device was tested at a time, this block diagram represents this.

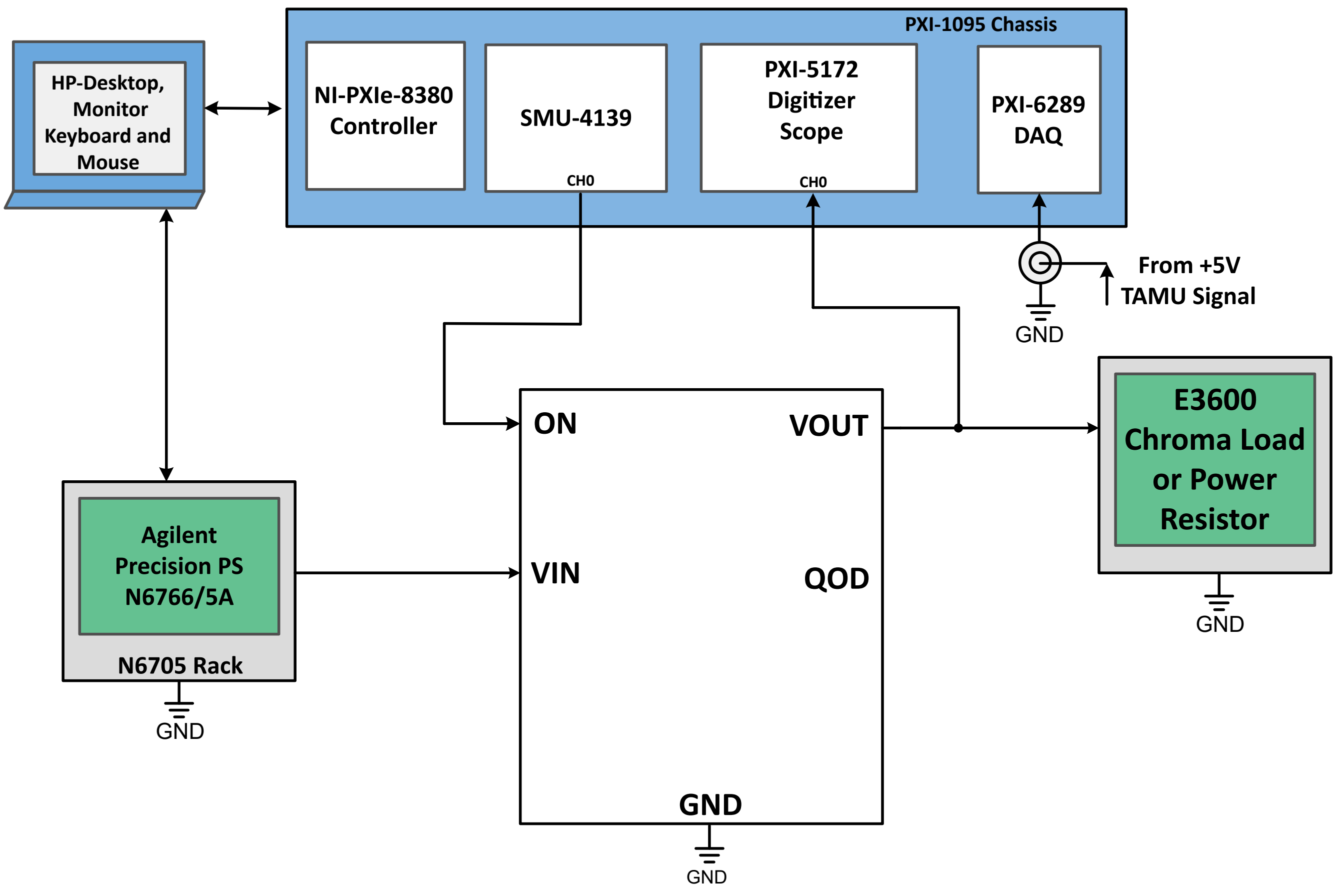


Figure 6-1. Block Diagram of SEE Test Setup With the TPS7H2221-SEP

7 Destructive Single-Event Effects (DSEE)

7.1 Single-Event Latch-up (SEL) Results

During SEL characterization, the device was heated using Closed Loop PID controlled heater (MISTRAL-6 SYSTEM 120V 2400W), maintaining the DUT temperature at 125°C. The die temperature was verified using a IR-camera (see Figure 3-3).

The species used for the SEL testing was Xenon (^{129}Xe) and Silver (^{109}Ag) with an angle-of-incidence of 0° for an LET_{EFF} = 42.7 and 46.8 MeV·cm^2/mg (for more details refer to Section 5). The kinetic energy in the vacuum for ^{129}Xe is 3.197 GeV (25-MeV/amu line) and for ^{109}Ag is 1.634 GeV (15-MeV/nucleon line). Flux of approximately 10^5 ions/cm^2·s and a fluence of approximately 10^7 ions/cm^2 were used for the five runs. Run duration to achieve this fluence was approximately 2 minutes. The five devices were powered up and exposed to the heavy-ions using the maximum recommended voltage of 5.5-V and loaded to 1.25-A using a 4.4-Ω power resistor or the Chroma E-Load in constant resistance (CR) mode at the same resistance value.

No SEL events were observed during all five runs, indicating that the TPS7H2221-SEP is SEL-free. Table 7-1 shows the SEL test conditions and results. Figure 7-1 shows a plot of the current vs time for run # 1.

Table 7-1. Summary of TPS7H2221-SEP SEL Test Condition and Results

RUN #	UNIT #	Load Type	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	SEL Event Occured?
1	1	Discrete Power Resistor	^{129}Xe	42.7	1.07×10^5	9.99×10^6	No
2	2	Discrete Power Resistor	^{129}Xe	42.7	1.17×10^5	9.96×10^6	No
3	3	Chroma (Constant Resistance)	^{129}Xe	42.7	9.77×10^4	1×10^7	No
4	4	Chroma (Constant Resistance)	^{109}Ag	46.8	1.15 x 10^5	1×10^7	No
5	5	Chroma (Constant Resistance)	^{109}Ag	46.8	1.10 x 10^5	1×10^7	No

Using the MFTF method described in *Single-Event Effects (SEE) Confidence Interval Calculations* application report and combining (or summing) the fluences for the three runs at ^{129}Xe, V_{IN} = 5.5 V @ 125°C (3 × 10^7), and the two runs at ^{109}Ag, V_{IN} = 5.5 V @ 125°C (2 × 10^7), the upper-bound cross sections (using a 95% confidence level) are calculated as:

$\sigma_{SEL} \leq 1.197 \times 10^{-7}$ cm²/device for LET_{EFF} = 42.7 MeV·cm²/mg and T = 125°C.

$\sigma_{SEL} \leq 1.844 \times 10^{-7}$ cm²/device for LET_{EFF} = 46.8 MeV·cm²/mg and T = 125°C.

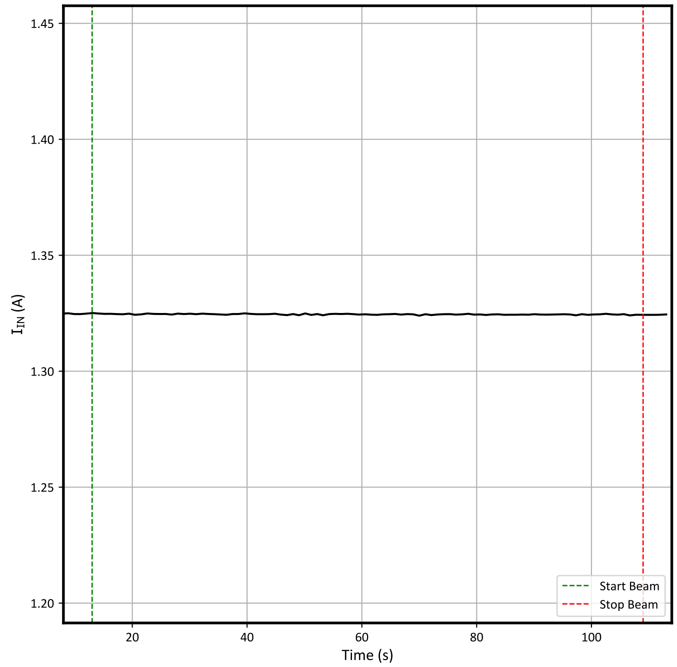


Figure 7-1. Current vs Time for Run # 1 of the TPS7H2221-SEP at T = 125°C

7.2 Single-Event Burnout (SEB) and Single-Event Gate Rupture (SEGR) Results

During the SEB/SEGR characterization, the device was tested at around 25°C.

The species used for the SEB/SEGR testing was a Xenon (^{129}Xe) ion and a Silver (^{109}Ag) with an angle-of-incidence of 0° for an LET_{EFF} = 42.7 and 46.8 MeV·cm^2/mg (for more details refer to Section 5). The kinetic energy in the vacuum for this ^{129}Xe is 3.197 GeV (25-MeV/amu line) and for ^{109}Ag is 1.634 GeV (15-MeV/nucleon line). Flux of approximately 10^5 ions/cm^2·s and a fluence of approximately 10^7 ions/cm^2 were used for the ten runs. Run duration to achieve this fluence was approximately 2 minutes. The five devices were powered up using the recommended maximum voltage of 5.5-V and loaded to 1.25-A using either the power resistor or the chroma load in CR mode. The TPS7H2221-SEP was tested under enabled and disabled modes, the device was disabled by using the ON pin forcing ON to 0 V through the PXIe-4139 SMU. The power resistor or Chroma E-Load were connected, even when the device was disabled, to help differentiate if an SET momentarily activated the device under the heavy-ion irradiation. During SEB/SEGR testing with the device "disabled", no V_{OUT} transient or input current events were observed. No SEB/SEGR events were observed during all ten runs, indicating that the TPS7H2221-SEP is SEB/SEGR-free up to LET_{EFF} = 46.8 MeV·cm^2/mg and across the full electrical specifications. Table 7-2 shows the SEB/SEGR test conditions and results. Figure 7-2 shows a plot of the current vs time for run # 6 (Enabled) and Figure 7-3 for run # 7 (Disabled).

Table 7-2. Summary of TPS7H2221-SEP SEB Test Condition and Results

RUN #	UNIT #	Load Type	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	ENABLED STATUS	SEB Event Occured?
6	1	Discrete Power Resistor	^{129}Xe	42.7	9.25×10^4	1×10^7	Enabled	No
7	1	Discrete Power Resistor	^{129}Xe	42.7	1×10^5	1×10^7	Disabled	No
8	2	Discrete Power Resistor	^{129}Xe	42.7	1.15×10^5	1×10^7	Enabled	No
9	2	Discrete Power Resistor	^{129}Xe	42.7	1.16×10^5	1×10^7	Disabled	No
10	3	Chroma (Constant Resistance)	^{129}Xe	42.7	9.77×10^4	1×10^7	Enabled	No
11	3	Chroma (Constant Resistance)	^{129}Xe	42.7	8.70×10^4	1×10^7	Disabled	No
12	4	Chroma (Constant Resistance)	^{109}Ag	46.8	1.22 x 10^5	1×10^7	Enabled	No
13	4	Chroma (Constant Resistance)	^{109}Ag	46.8	1.26 x 10^5	9.95 x 10^6	Disabled	No
14	5	Chroma (Constant Resistance)	^{109}Ag	46.8	1.05 x 10^5	1×10^7	Enabled	No
15	5	Chroma (Constant Resistance)	^{109}Ag	46.8	1.09 x 10^5	9.95 x 10^6	Disabled	No

Using the MFTF method described in *Single-Event Effects (SEE) Confidence Interval Calculations* application report and combining (or summing) the fluences of the six ^{129}Xe runs @ 25°C (6 × 10^7) and the four ^{109}Ag runs @ 25°C (4 × 10^7), the upper-bound cross sections (using a 95% confidence level) are calculated as:

$\sigma_{SEB} \leq 6.15 \times 10^{-8}$ cm^2/device for LET_{EFF} = 42.7 MeV·cm^2/mg and T ≤ 25°C.

$\sigma_{SEB} \leq 9.24 \times 10^{-8}$ cm^2/device for LET_{EFF} = 46.8 MeV·cm^2/mg and T ≤ 25°C.

The dips in current are associated with SETs which are discussed further in the SET section. All current excursions were fully recoverable with no external intervention.

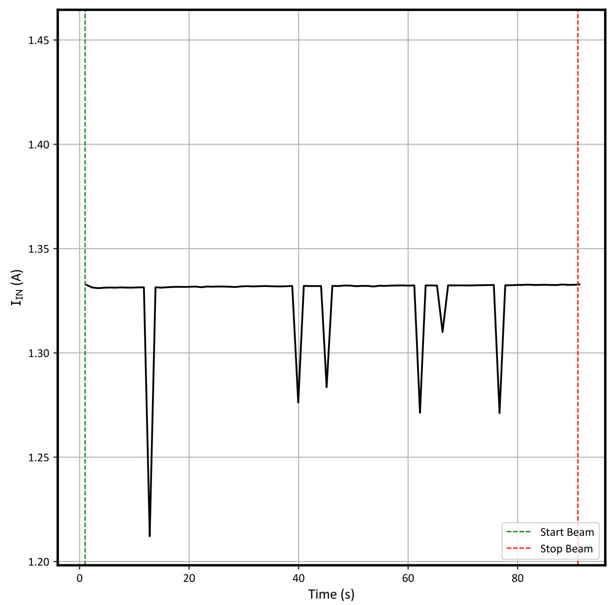


Figure 7-2. Current vs Time for Run # 4 (Enabled) for the TPS7H2221-SEP

The TPS7H2221-SEP have a typical shutdown current of 2nA at 25 °C, however the N6766A power supply resolution is on the mA range, for this reason the plot here shows the noise floor of the equipment. As the load was connected at all times, this prove that during the SEB-OFF no Burn-Out or momentary enabling of the pass element happened during the heavy-ion exposure.

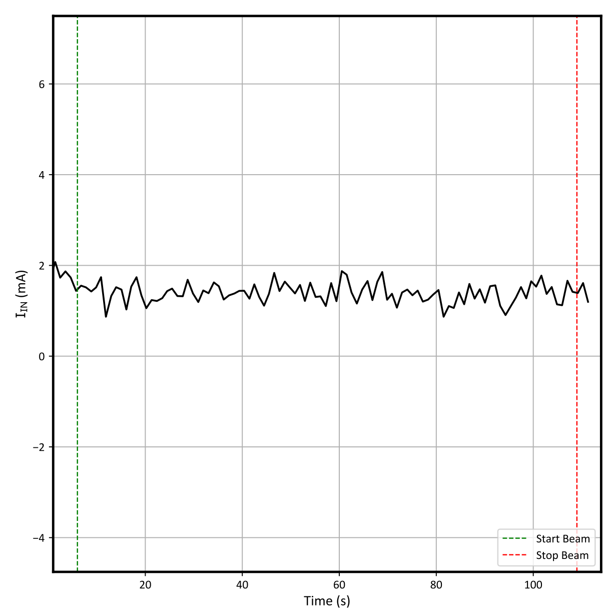


Figure 7-3. Current vs Time for Run # 5 (Disabled) for the TPS7H2221-SEP

8 Single-Event Transients (SET) and Single Event Functional Interrupt (SEFI)

8.1 Single Event Transient (SET)

SETs are defined as heavy-ion-induced transients upsets on V_{OUT} of the TPS7H2221-SEP. The species used for the SET testing was a Xenon (^{129}Xe) ion and a Silver (^{109}Ag) with an angle-of-incidence of 0° for an LET_{EFF} = 42.7 and 46.8 MeV·cm²/mg, for more details refer to Section 5. Flux of approximately 10^4 ions/cm²·s and a fluence of approximately 3 × 10^6 ions/cm² were used for the ten ^{129}Xe SET runs. Flux of approximately 10^5 ions/cm²·s and a fluence of approximately 10^7 ions/cm² were used for the six ^{109}Ag SET runs.

V_{OUT} SETs were characterized using a window trigger of ±3% around the nominal output voltage. The devices were characterized at V_{IN} = 1.8-V, 3.3-V, and 5-V. The output load was set to either 100-mA, 500-mA, or 1.25-A using a Chroma E-Load in constant resistance (CR) mode. To capture the SETs an NI-PXIe-5172 scope card was used to continuously monitor the V_{OUT}. The output voltage was monitored by using the TP2 (U1) and the TP7 (U2) test points on the EVM. The scope triggering from V_{OUT} was programmed to record 50k samples with a sample rate of 10 Mega samples per second (MS/s) in case of an event (trigger). The scope was programmed to record 20% of the data before (pre) the trigger.

Under heavy-ions, the TPS7H2221-SEP exhibits transient upsets that were fully recoverable without the need for external intervention.

Test conditions and results are summarized in Table 8-1. Histograms for the $VOUT_{SET}$ transient time are shown in Table 8-1. There is no histogram for the $VOUT_{SET}$ peak percentage as all SETs dropped to 0-V before fully recovering as shown in the worst case transient image.Table 8-1 shows typical time domain plots for all of the observed SETs.

Table 8-1. Summary of TPS7H2221-SEP SET Test Condition and Results

Note that for the SET cases where the ^{109}Ag ion was used, the total fluence per run was over 3 times as long as the runs with ^{129}Xe which accounts for the increase in number of transients per run.

RUN #	UNIT #	ION	LET_{EFF}(MeV·cm²/mg)	FLUX(ions·cm²/mg)	FLUENCE (# ions)	V_{IN}(V)	LOAD (A)	$VOUT_{SET}$ (#) ≥ ±3%
16	1	^{129}Xe	42.7	1.12 × 10^4	3 × 10^6	1.8	0.1	142
17	1	^{129}Xe	42.7	1.15 × 10^4	3 × 10^6	3.3	0.1	126
18	1	^{129}Xe	42.7	1.13 × 10^4	3 × 10^6	3.3	1.25	116
19	1	^{129}Xe	42.7	1.21 × 10^4	3 × 10^6	5	0.1	112
20	1	^{129}Xe	42.7	1.10 × 10^4	3 × 10^6	5	1.25	98
21	2	^{129}Xe	42.7	1.19 × 10^4	3 × 10^6	1.8	0.1	138
22	2	^{129}Xe	42.7	1.15 × 10^4	3 × 10^6	3.3	0.1	113
23	2	^{129}Xe	42.7	1.13 × 10^4	3 × 10^6	3.3	1.25	130
24	2	^{129}Xe	42.7	1.20 × 10^4	3 × 10^6	5	0.1	103
25	2	^{129}Xe	42.7	1.10 × 10^4	2.99 × 10^6	5	1.25	106
26	3	^{109}Ag	46.8	1.08 x 10^5	9.94 x 10^6	3.3	1.25	395
27	3	^{109}Ag	46.8	1.08 x 10^5	1 x 10^7	5	1.25	321
28	3	^{109}Ag	46.8	1.03 x 10^5	9.95 x 10^6	1.8	.5	472
29	4	^{109}Ag	46.8	1.11 x 10^5	9.98 x 10^6	3.3	1.25	377
30	4	^{109}Ag	46.8	1.02 x 10^5	9.99 x 10^6	5	1.25	329
31	4	^{109}Ag	46.8	1.09 x 10^5	9.98 x 10^6	1.8	.5	451

Using the MFTF method described in *Single-Event Effects (SEE) Confidence Interval Calculations* application report, the upper-bound cross section (using a 95% confidence level) is calculated for the different SETs as shown in Table 8-2 and Table 8-2 .

Table 8-2. Upper Bound Cross Section at 95% Confidence Interval

SET TYPE	ION	V_{IN} (V)	# UPSETS	UPPER BOUND CROSS SECTION (cm^2/device)
$VOUT_{SET} \geq \|3\%\|$	^{129}Xe	1.8	280	5.25×10^{-5}
$VOUT_{SET} \geq \|3\%\|$	^{129}Xe	3.3	485	4.42×10^{-5}
$VOUT_{SET} \geq \|3\%\|$	^{129}Xe	5	419	3.84×10^{-5}
$VOUT_{SET} \geq \|3\%\|$	^{109}Ag	1.8	923	5.13×10^{-5}
$VOUT_{SET} \geq \|3\%\|$	^{109}Ag	3.3	772	4.31×10^{-5}
$VOUT_{SET} \geq \|3\%\|$	^{109}Ag	5	650	3.53×10^{-5}

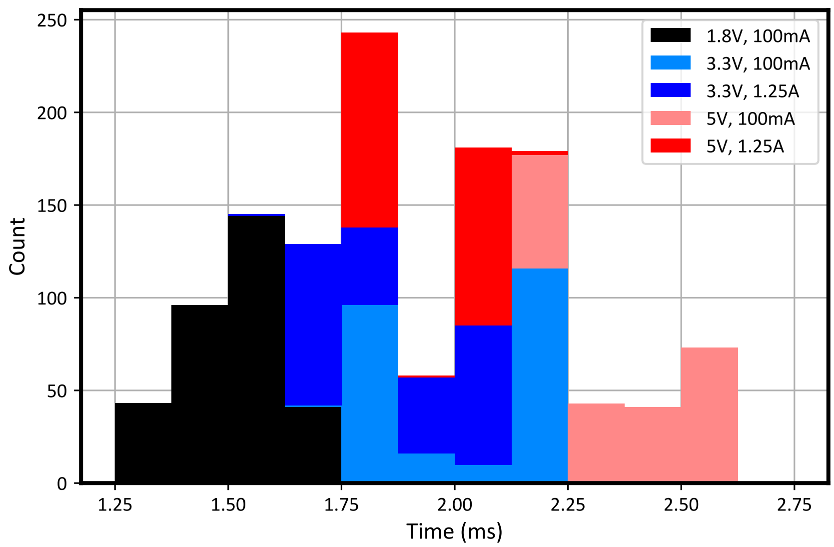


Figure 8-1. Histogram of the Transient Time for V_{OUT} SETs at LET_{EFF} = 42.7 MeV·cm²/mg

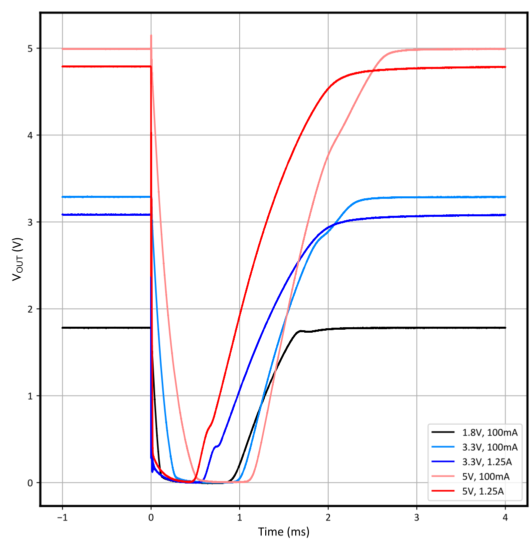


Figure 8-2. Typical $VOUT_{SET}$ at LET_{EFF} = 42.7 MeV·cm²/mg

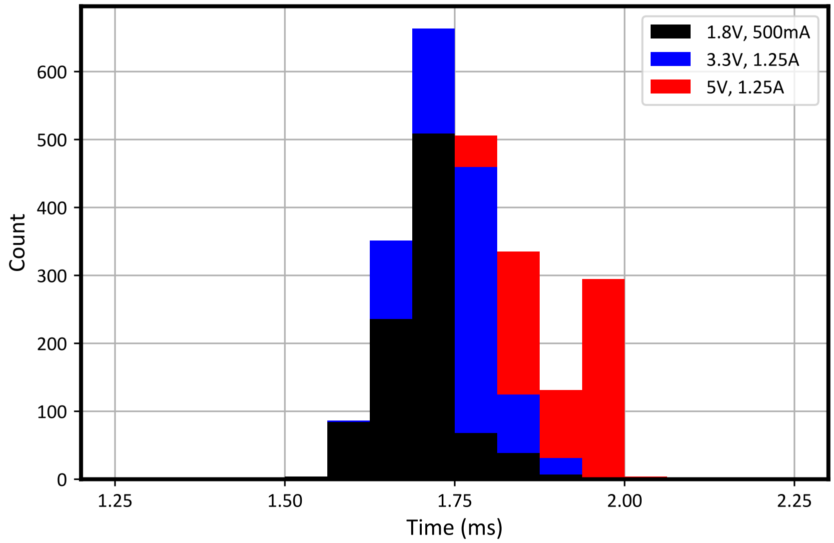


Figure 8-3. Histogram of the Transient Time for V_{OUT} SETs at LET_{EFF} = 46.8 MeV·cm^2/mg

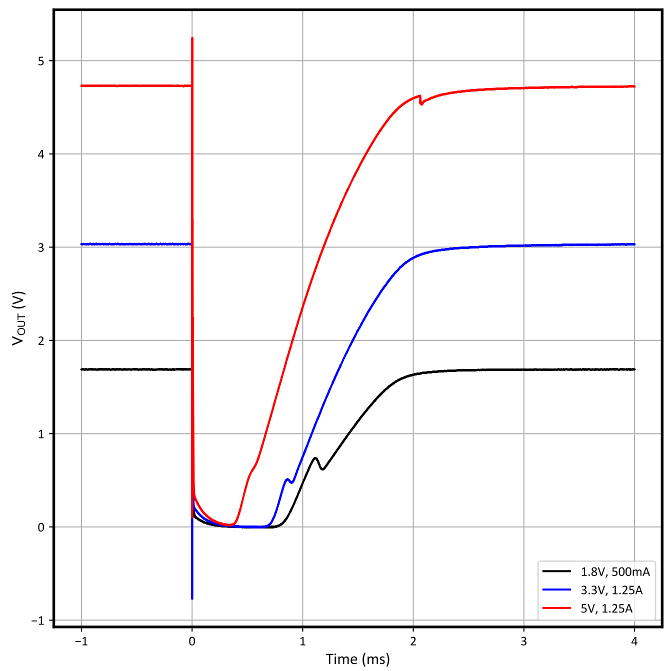


Figure 8-4. Typical $VOUT_{SET}$ at LET_{EFF} = 46.8 MeV·cm^2/mg

8.2 Single Event Functional Interrupt (SEFI)

SEFIs are defined as cases where a device stops functioning normally for an extended period of time (longer than a transient) and in some cases requires a power reset in order to allow the device to recover. During testing there was a concern of potential SEFIs when the device was operating with low voltage (<3.1-V) and high load (~1.25-A). In order to test this, six different devices were tested across a range of input conditions. Testing included keeping the load at 1.25-A while sweeping the input voltage down from 3.1-V until a SEFI occured. The LET for all tests was kept at either 42.7 or 46.8 MeV·cm^2/mg using ^{129}Xe or ^{109}Ag at incident angle with a flux of ≈10^4 or 10^5 to a flunce range of 10^6 to 10^7. Test results and an example of the SEFI are reported and discussed below.

For testing done with the ^{109}Ag Silver ion the QOD pin was tested under two different conditions. The first was tying it high to V_{OUT} and the second was tying it high to P_{GOOD} with a 2 kΩ resistor. In the case where QOD was tied to V_{OUT} only V_{OUT} was monitored, under this test condition there were no observed differences in transient behavior. In the case where QOD was tied to P_{GOOD} the QOD pin was monitored seperately from V_{OUT}, under this test condition the transient behavior on QOD aligned with the transient behavior on V_{OUT} with no observable differences.

Table 8-3. Summary of TPS7H2221-SEP SEFI Test Condition and Results

For devices 3 and 4 fluence was only run to 1 x 10^6 as earlier results showed that the SEFI signature would occur well before 1 x 10^6.

Run #	Unit #	Ion	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	V_{IN} (V)	LOAD (A)	SEFI OCCURED?
32	1	^{129}Xe	42.7	1.19 x 10^4	3 x 10^6	3.1	1.25	No
33	1	^{129}Xe	42.7	1.12 x 10^4	3 x 10^6	2.9	1.25	No
34	1	^{129}Xe	42.7	1.16 x 10^4	3 x 10^6	2.7	1.25	No
35	1	^{129}Xe	42.7	1.13 x 10^4	7.33 x 10^5	1.8	1.25	Yes
36	2	^{129}Xe	42.7	1.16 x 10^4	3 x 10^6	2.7	1.25	No
37	2	^{129}Xe	42.7	1.07 x 10^4	3 x 10^6	2.6	1.25	No
38	2	^{129}Xe	42.7	1.08 x 10^4	3 x 10^6	2.5	1.25	No
39	2	^{129}Xe	42.7	1.10 x 10^4	3 x 10^6	2.4	1.25	No
40	2	^{129}Xe	42.7	1.20 x 10^4	6.61 x 10^5	1.8	1.25	Yes
41	3	^{129}Xe	42.7	1.19 x 10^4	1 x 10^6	1.8	1.25	No
42	3	^{129}Xe	42.7	1.36 x 10^4	1 x 10^6	1.6	1.25	No
43	4	^{129}Xe	42.7	1.06 x 10^4	1 x 10^6	1.6	1.25	No
44	4	^{129}Xe	42.7	1.03 x 10^4	1 x 10^6	1.6	1.25	No
45	5	^{109}Ag	46.8	1.06 x 10^5	1 x 10^7	2.4	1.25	No

Table 8-3. Summary of TPS7H2221-SEP SEFI Test Condition and Results (continued)

For devices 3 and 4 fluence was only run to 1 x 10^6 as earlier results showed that the SEFI signature would occur well before 1 x 10^6.

Run #	Unit #	Ion	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg)	FLUENCE (# ions)	V_{IN} (V)	LOAD (A)	SEFI OCCURED?
46	6	^{109}Ag	46.8	9.44 x 10^4	9.98 x 10^6	2.4	1.25	No

During SEFI occurance all behavior was non-destructive and was fixed by toggling the "ON" pin to reset the device.

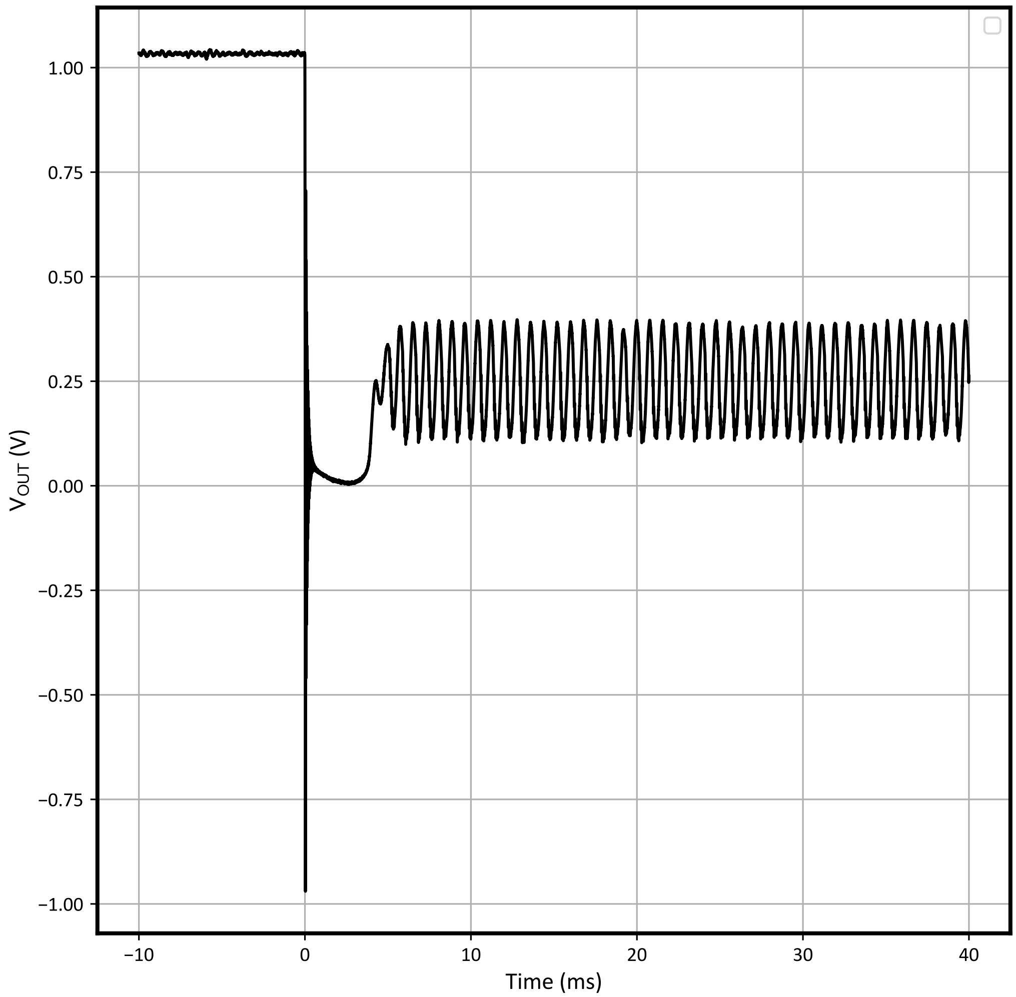


Figure 8-5. Typical TPS7H2221-SEP SEFI

The results show that there is part to part variation as to whether the SEFI occurs at V_{IN} = 1.8-V, however the device appears to be SEFI free at V_{IN} ≥ 2.4-V with the full 1.25-A load. This SEFI testing provides high likeliness that the device will be fully operational at max load with V_{IN} ≥ 2.4-V. Along with the six production samples that were tested, lookahead testing was conducted with four non-production samples that validate device functionality at this range. Although the device can be fully operational at V_{IN} = 1.6-V or 1.8-V some devices showed the SEFI behavior at this voltage level. Because of this it is unlikely that the device can operate at max load with these voltage levels while under the effects of radiation.

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* application report. 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 SEL and the SEB/SEGR, the event rate calculation for the SEL and the SEB/SEGR is shown on Table 9-1 and Table 9-2, respectively. **It is important to note that this number is for reference since no SEL or SEB/SEGR events were observed.**

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

Orbit Type	Onset LET_{EFF} (MeV-cm^2/mg)	CREME96 Integral FLUX (/day/cm^2)	σSAT (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	42.7	6.305×10^{-4}	1.197×10^{-7}	7.503×10^{-11}	3.126×10^{-3}	3.651×10^{7}
GEO		2.136×10^{-3}		2.542×10^{-10}	1.059×10^{-2}	1.078×10^{7}
LEO (ISS)	46.8	4.868×10^{-4}	1.844×10^{-7}	8.977×10^{-11}	3.740×10^{-3}	3.052×10^{7}
GEO		1.604×10^{-3}		2.957×10^{-10}	1.232×10^{-2}	9.264×10^{6}

Table 9-2. SEB/SEGR Event Rate Calculations for Worst-Week LEO and GEO Orbits

Orbit Type	Onset LET_{EFF} (MeV-cm^2/mg)	CREME96 Integral FLUX (/day/cm^2)	σSAT (cm^2)	Event Rate (/day)	Event Rate (FIT)	MTBE (Years)
LEO (ISS)	42.7	6.305×10^{-4}	6.15×10^{-8}	3.878×10^{-11}	1.616×10^{-3}	7.065×10^{7}
GEO		2.136×10^{-3}		1.313×10^{-10}	5.473×10^{-3}	2.086×10^{7}
LEO (ISS)	46.8	4.868×10^{-4}	9.24×10^{-8}	4.498×10^{-11}	1.874×10^{-3}	6.091×10^{7}
GEO		1.604×10^{-3}		1.482×10^{-10}	6.175×10^{-3}	1.849×10^{7}

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 TPS7H2221-SEP load switch. Heavy-ions with LET_{EFF} = 46.8 MeV·cm^2/mg were were used for the SEE characterization campaign. Flux of 10^4 or 10^5 ions/cm^2·s and fluences up to 3 x 10^6 or 1 × 10^7 ions/cm^2 per run were used for the characterization. The SEE results demonstrated that the TPS7H2221-SEP load switch is free of destructive SEB events and SEL-free up to LET_{EFF} = 46.8 MeV·cm^2/mg and across the full electrical specifications. Transients at LET_{EFF} = 46.8 MeV·cm^2/mg on V_{OUT} are presented and discussed. CREME96-based worst-week event-rate calculations for LEO(ISS) and GEO orbits for the DSEE are presented for reference.

A Appendix: Total Ionizing Dose from SEE Experiments

The production TPS7H2221-SEP Load Switch is radiation lot acceptance tested (RLAT) to a total ionizing dose (TID) of 20 krad(Si) (characterized to 30 krad(Si)). In the course of the SEE testing, the heavy-ion exposures delivered ≈10 krad(Si) per 10^7 ions/cm^2 run. The cumulative TID exposure over all runs was determined to be between 3 krad(Si) to 20 krad(Si), for each device. All production TPS7H2221-SEP devices sued in the study described in this report were fully-functional after the heavy-ion SEE testing campaign.

B Appendix: References

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