Radiation Report

TPS7H3014-SEP Single-Event Effects (SEE)

TEXAS INSTRUMENTS

ABSTRACT

The purpose of this study is to characterize the Single-Event Effects (SEE) performance due to heavy-ion irradiation of the TPS7H3014-SEP. Heavy-ions with LET_{EFF} of 48 MeV·cm^2/mg were used to irradiate production devices. Flux of ≈10^5 ions/cm^2·s and fluence of ≈10^7 ions/cm^2 per run were used for the characterization. The results demonstrate the TPS7H3014-SEP is SEL-free and SEB/SEGR-free at T = 125°C and T = 25°C, respectively. The TPS7H3014-SEP was also tested for SET at T = 25°C, results demonstrate the device is SET and SEFI free.

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1 Introduction

The TPS7H3014-SEP is an integrated 3V to 14V, four channel radiation-hardness assured power-supply sequencer. The channel count can be incremented as needed for the application by connecting multiple ICs in a daisy-chain configuration. The device features sequence up and reverse sequence down control signals (UP and DOWN), SEQ-DONE and PWRGD flags to monitor the sequence and power status of the monitored power tree. Other features for the device include:

- A 599mV ± 1% threshold voltage
- 24µA ± 3% hysteresis current
- Common programmable (268µs to 23.37ms) delay timer
  - Valid during sequence up and down
- Time-to-regulation programmable timer (264µs to 23.63ms) to track rising voltage on $SENSE_X$
  - Valid only during sequence up
- Open drain FAULT detection pin to monitor internally generated faults

The device is offered in a 24-pin plastic (TSSOP) package. 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 TPS7H3014-SEP product page.

Table 1-1. Overview Information

DESCRIPTION(1)	DEVICE INFORMATION
TI Part Number	TPS7H3014-SEP
Orderable Number	TPS7H3014MPWTSEP
Device Function	4-channel sequencer
Technology	LBC7 (Linear BiCMOS 7)
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University (15MeV/nucleon)
Heavy Ion Fluence per Run	1.00×10^7 ions/cm^2
Irradiation Temperature	25°C (for SEB/SEGR testing), 25°C (for SET testing), and 125°C (for SEL testing)

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2 Single-Event Effects (SEE)

The primary concern for the TPS7H3014-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 TPS7H3014-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. During the testing of the TPS7H3014-SEP, a total of three units were exposed under worst-case bias conditions for SEL. The TPS7H3014-SEP did not exhibit any SEL with heavy-ions with LET_{EFF} = 48 MeV·cm^2 /mg at flux of ≈10^5 ions/cm^2 ·s, fluence of ≈10^7 ions/cm^2, and a die temperature of 125°C.

The TPS7H3014-SEP was evaluated for SEB/SEGR at a maximum voltage of 14V (V_{IN}) in the waiting to sequence up (all outputs low) and waiting to sequence down (all outputs high) states. Because it has been shown that the MOSFET susceptibility to burnout decrement with temperature [5], the device was evaluated while operating under room temperatures. The device was tested with no external thermal control device. During the SEB/SEGR testing, not a single current event was observed, demonstrating that the TPS7H3014-SP is SEB/SEGR-free up to LET_{EFF} = 48 MeV·cm^2/mg at a flux of ≈10^5 ions/cm^2·s, fluence of ≈10^7 ions/cm^2, and a die temperature of ≈25°C.

The TPS7H3014-SEP was tested under nominal input conditions for SET. During the testing of three devices, not a single transient was recorded, showing that the TPS7H3014-SEP is both transient free and SEFI free. To see more details please refer to Section 8.

The forcing conditions for the different DSEE and SET testing are shown in Table 2-1.

Table 2-1. SEE Biasing Conditions

DSEE TYPE	VIN (V)	VPULL_UP (V)	VUP (V)	T_J (°C)	FLUX (ions/cm^2·s)	FLUENCE (ions/cm^2)
SEL	14	7	3.3	125	10^5/run	10^7/run
SEB/SEGR	14	7	[0,3.3]	25		
SET	5	3.3	[0,1]	25		

3 Device and Test Board Information

The TPS7H3014-SEP is packaged in a 24-pin TSSOP plastic package as shown in Figure 3-1. The TPS7H3014-SEP evaluation module was used to evaluate the performance and characteristics of the TPS7H3014-SEP under heavy ion radiation. The TPS7H3014EVM (Evaluation Module) is shown in Figure 3-2. The actual EVM BOM was modified from the original (or default) to set the EN_X to $SENSE_X$ resistor divider to the correct values to attain the desired overdrive voltage on $SENSE_X$. Two different configurations were used during the heavy-ions test campaign, the details are provided on Figure 3-3 and Figure 3-4.

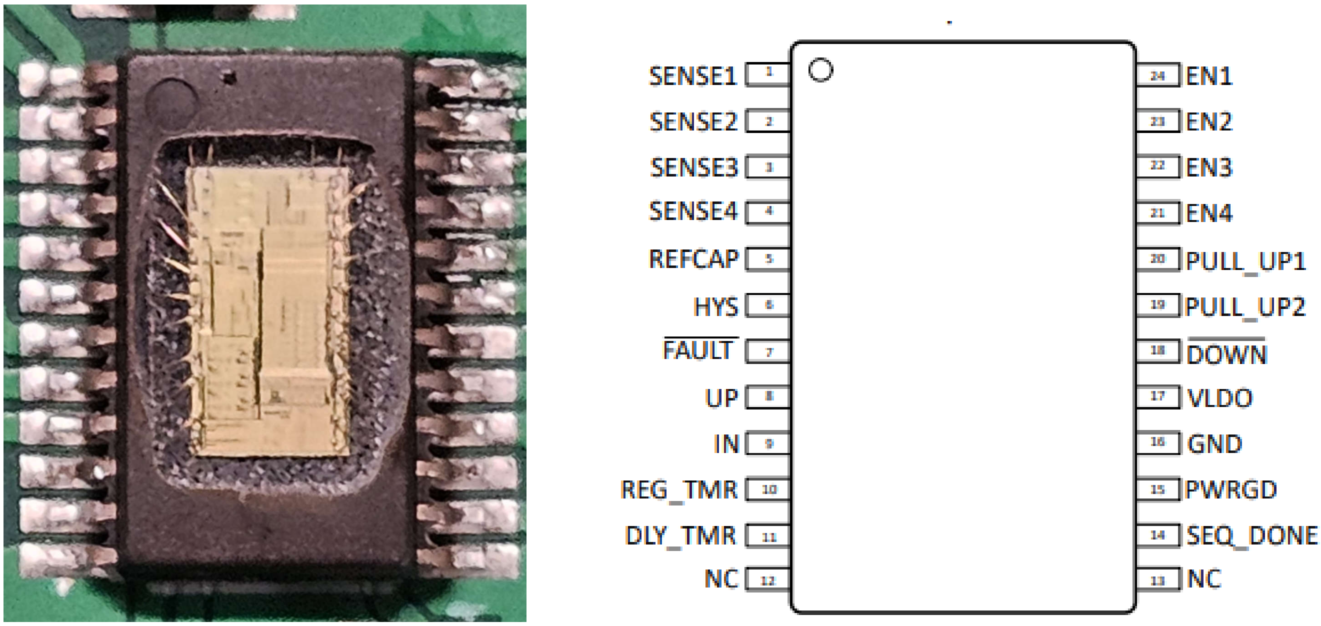


Figure 3-1. Photograph of Delidded TPS7H3014-SEP [Left] and Pinout Diagram [Right]

Note: The package was delidded to reveal the die face for all heavy-ion testing.

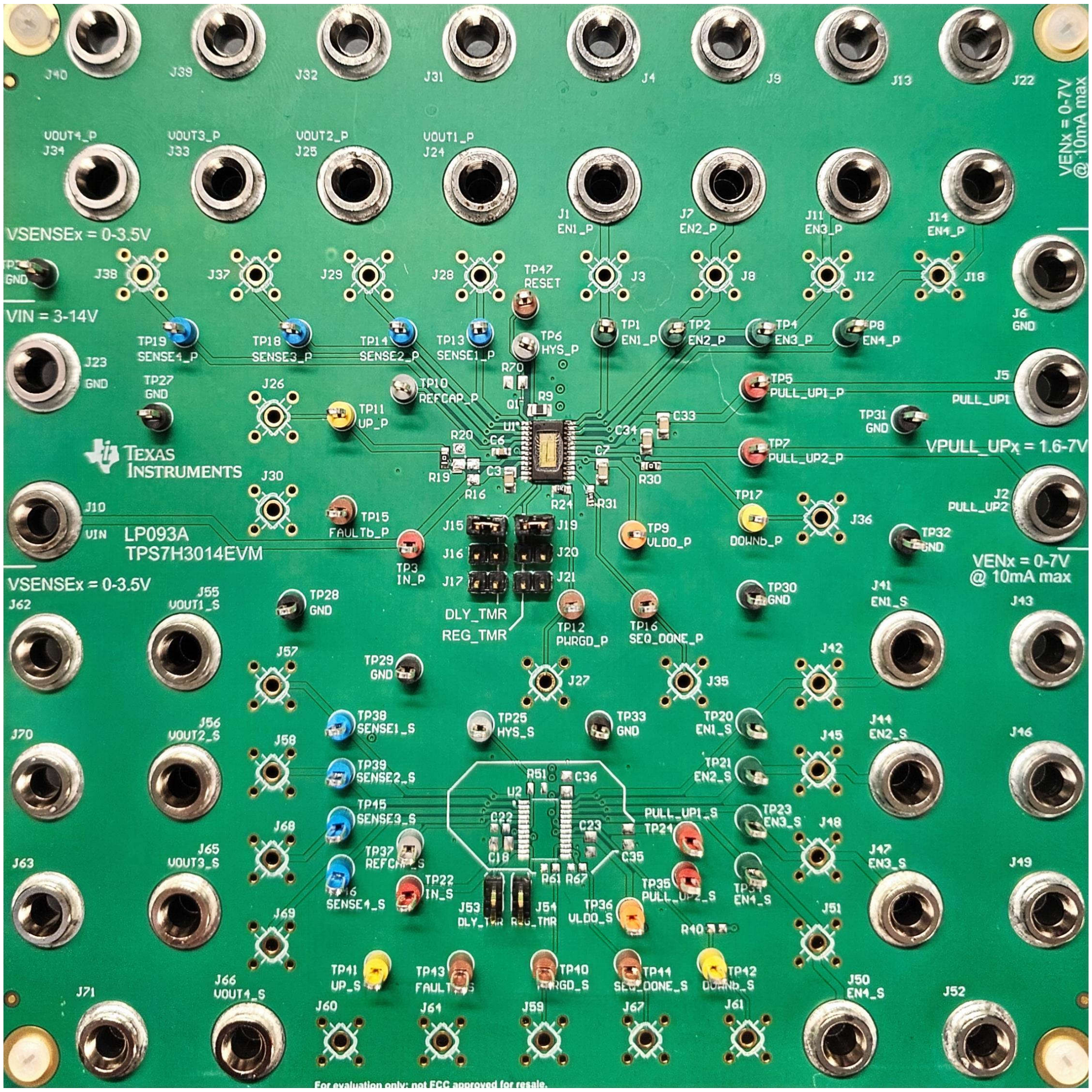


Figure 3-2. TPS7H3014-SEP EVM Top View

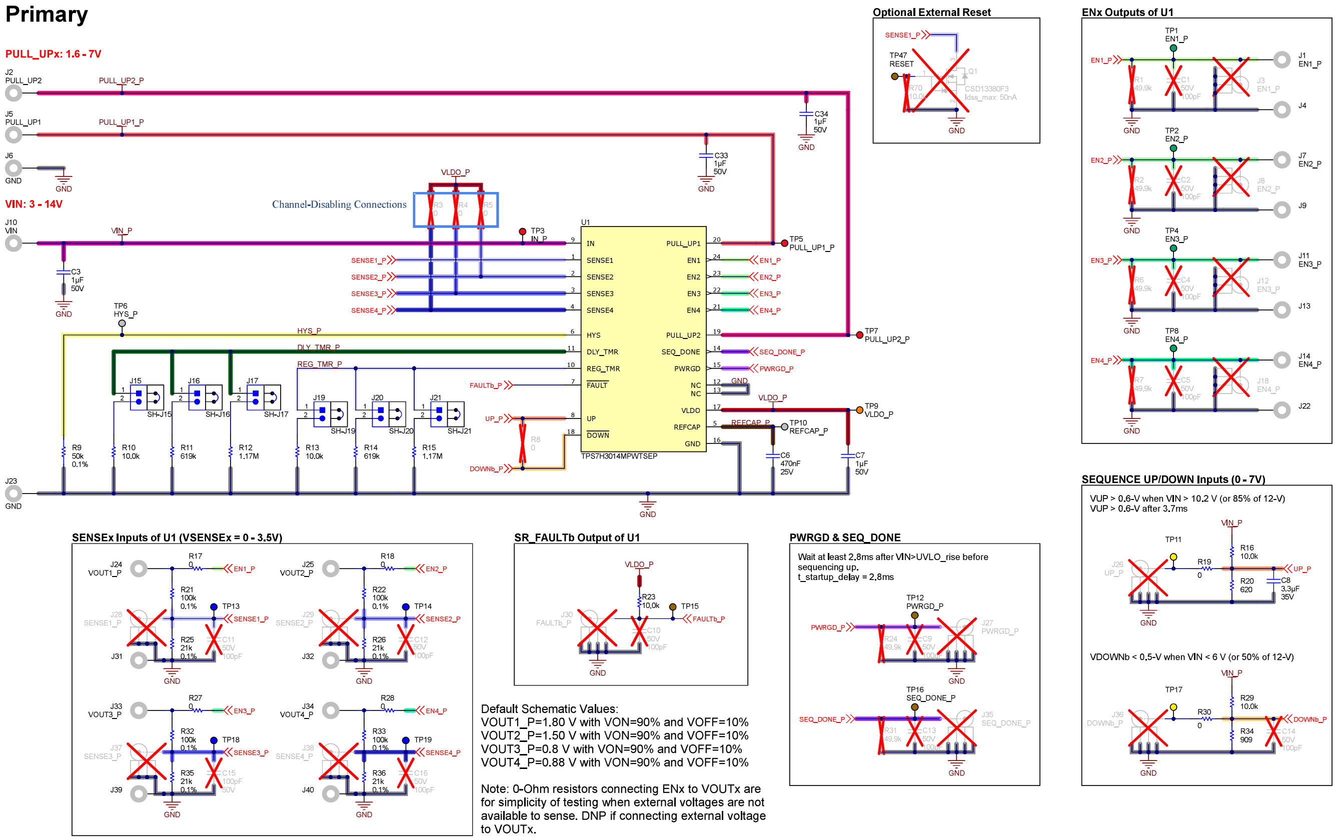


Figure 3-3. TPS7H3014-SEP EVM Schematic for DSEE Testing

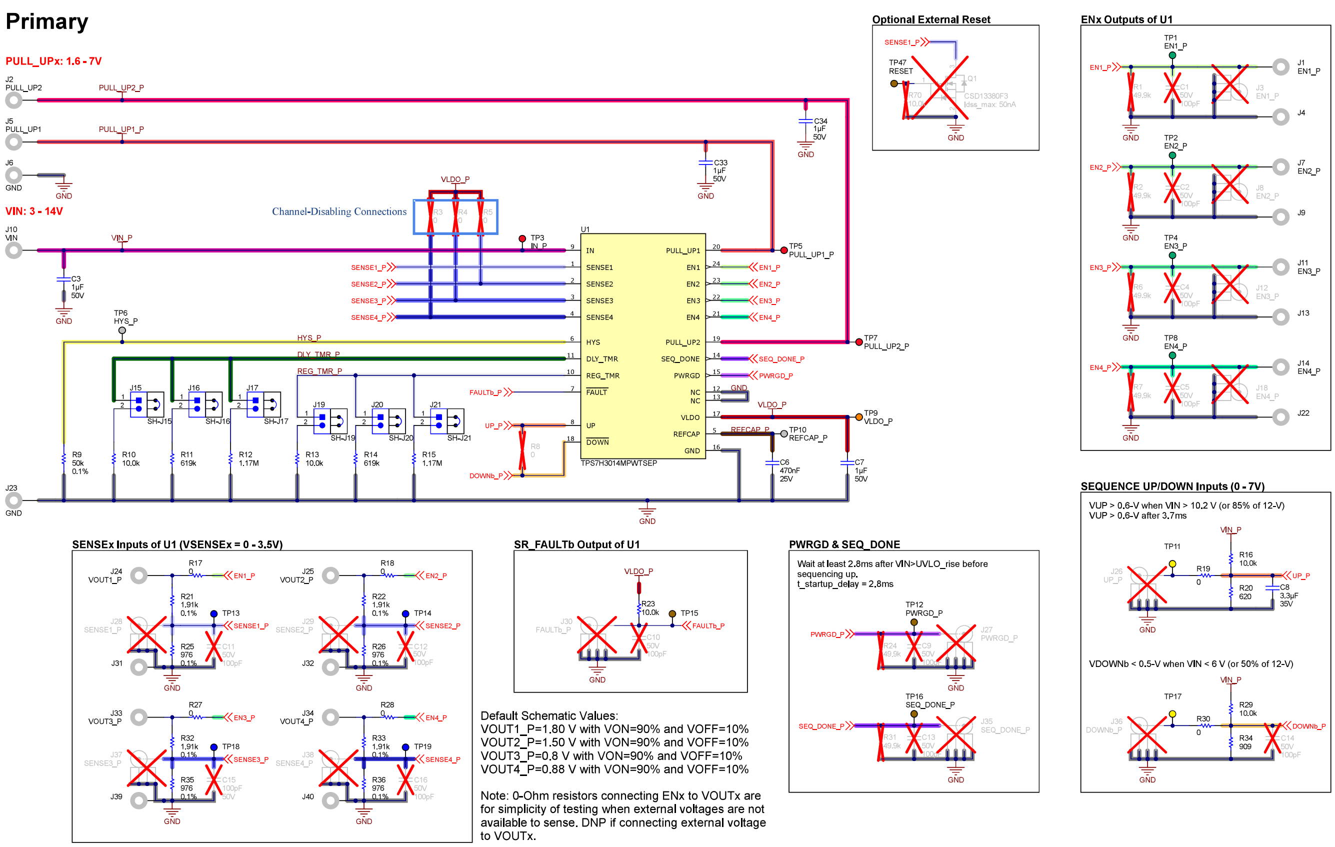


Figure 3-4. TPS7H3014-SEP EVM Schematic for SET Testing

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 1in 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 these studies, ion flux of 9.92×10^4 to 1.50×10^5 ions/cm^2·s were used to provide heavy-ion fluences of 1.00×10^7 ions/cm^2.

For the experiments conducted on this report ^{109}Ag was used to obtain LET_{EFF} of 48 MeV·cm^2/mg. The total kinetic energy for each of the ion was:

- ^{109}Ag = 1.635 GeV (15MeV/nucleon)
  - Ion uniformity for these experiments was between 95% and 97%

Figure 4-1 shows the TPS7H3014EVM used for the data collection at the TAMU facility. Although not visible in this photo, 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. The in-air gap between the device and the ion beam port window was maintained at 40mm for all runs.

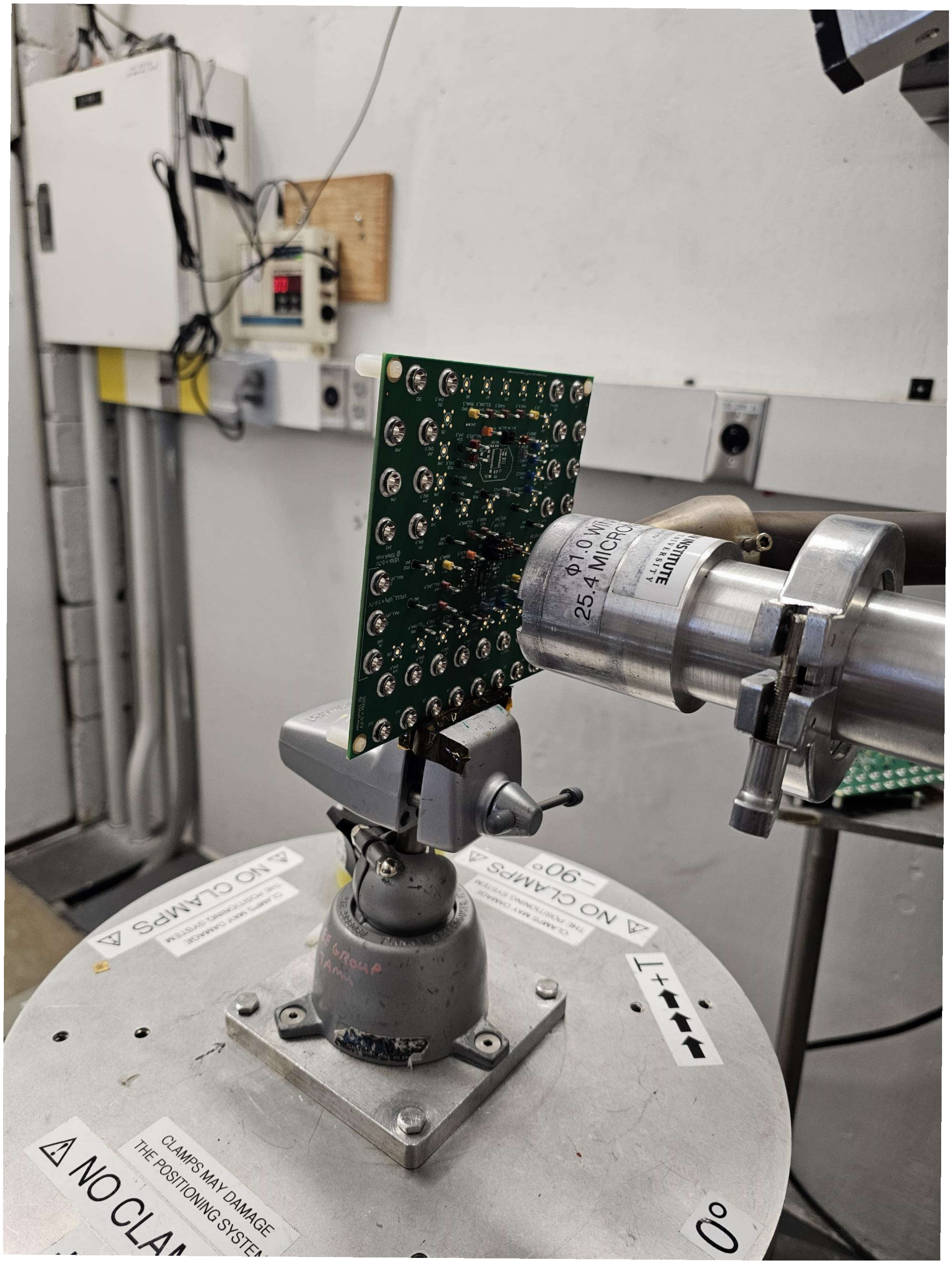


Figure 4-1. Photograph of the TPS7H3014EVM in Front of the Heavy-Ion Beam Exit Port at the Texas A&M Cyclotron

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

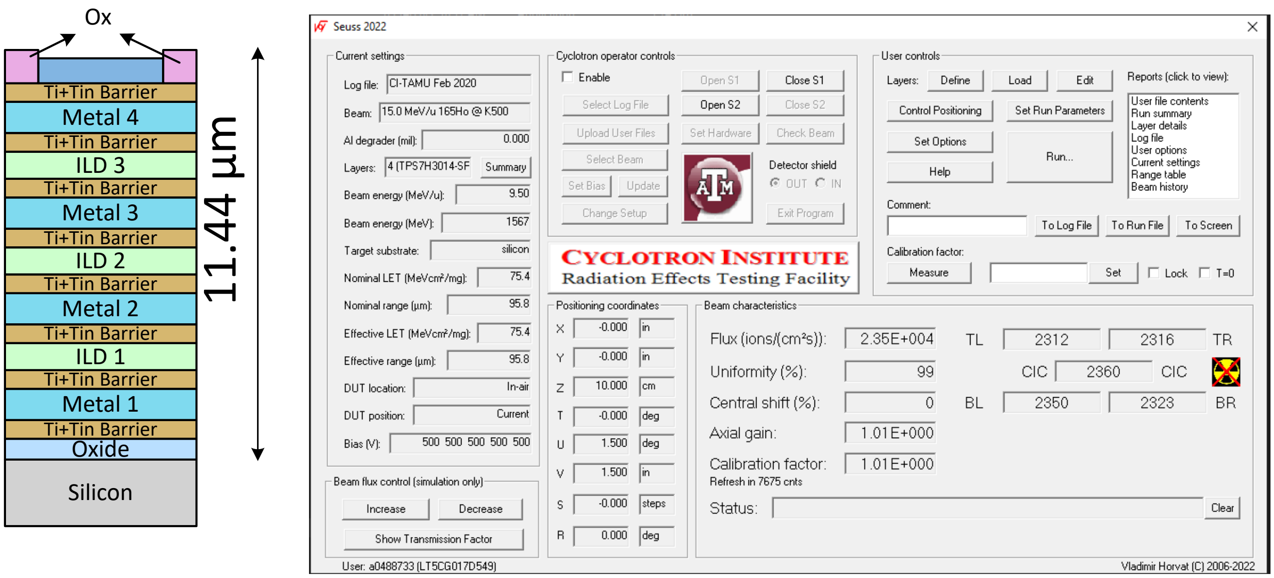


Figure 5-1. Generalized Cross-Section of the LBC7 Technology BEOL Stack on the TPS7H3014-SEP [Left] and SEUSS 2020 Application Used to Determine Key Ion Parameters [Right]

The TPS7H3014-SEP is fabricated in the TI Linear BiCMOS 250nm process with a back-end-of-line (BEOL) stack consisting of four levels of standard thickness aluminum. The total stack height from the surface of the passivation to the silicon surface is 11.44µm 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 40mm air gap, and the BEOL stack over the TPS7H3014-SEP, the effective LET (LET$_{EFF}$) at the surface of the silicon substrate and the depth 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.

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

ION TYPE	BEAM ENERGY (MeV/nucleon)	ANGLE OF INCIDENCE	DEGRADER STEPS (#)	DEGRADER ANGLE	RANGE IN SILICON (µm)	LET$_{EFF}$ (MeV·cm^2/mg)
^{109}Ag	15	0	0	0	97.2	48

6 Test Setup and Procedures

There were four input supplies used to provide power to the TPS7H3014-SEP. The voltage values and the model of the used equipment per the SEE test type is presented in Table 6-1.

Table 6-1. Details of Power Supplies Used for the Heavy-Ion Test Campaign of the TPS7H3014-SEP

VOLTAGE NAME	VOLTAGE (V)	SEE TEST TYPE	POWER SUPPLY MODEL
VIN	14	SEL, SEB/SEGR	N6766A
VPULL_UP1	7		PXIe-4139
VPULL_UP2	7		
VUP	0, 3.3		
VIN	5	SET	N6766A
VPULL_UP1	3.3		PXIe-4139
VPULL_UP2	3.3		
VUP	0, 1		

As discussed in Section 3 the TPS7H3014-SEP was tested (or evaluated) under heavy-ions using three unique configurations.

1. For DSEE the device was tested under the configuration shown in Figure 3-3. We refer to this configuration as the loopback. In loopback mode ENx is connected to SENSEx via a resistor divider for automatic sequence up and down. EN_X was tied to $SENSE_X$ using a resistor divider with R_{TOP} = 100kΩ and R_{BOTTOM} = 21kΩ. Under this configuration the overdrive The overdrive is referring to the difference between the steady-state voltage when the hysteresis current is active and the internal V_{TH_SENSEx} reference voltage (599mV typically). For example, for an overdrive voltage of 1V the steady-state voltage is 1.599V when the I_{HYS_SENSEx} is active. voltage is 1V (typically).
2. For SET the device was tested under the configuration shown in Figure 3-4. This testing was completed in the loopback configuration. EN_X was tied to $SENSE_X$ using a resistor divider with R_{TOP} = 1.91kΩ and R_{BOTTOM} = 976Ω. Under this configuration the overdrive voltage is ±20mV (typically). The device was tested under:
   a. Waiting to Sequence UP State (with –20mV).
   b. Waiting to Sequence DOWN State (with+20mV).

Transients were monitored on EN1, EN4, and FAULT. The equipment used and the trigger details are summarized in Table 6-2. The device was tested for transients under the Waiting to Sequence UP and Waiting to Sequence DOWN states. This was done to ensure the device will not activate/deactivate any downstream device (typically a POL) connected to it.

Table 6-2. Summary of Oscilloscope and Conditions Used for the SEE Test Campaign of the TPS7H3014-SEP

SIGNAL NAME	EQUIPMENT USED TO MONITOR SIGNAL	TRIGGER TYPE	TRIGGER VALUE WHEN SIGNAL WAS HIGH (%)	TRIGGER VALUE WHEN SIGNAL WAS LOW (V)
EN1	PXIe-5172	Falling, edge Rising, edge	–20 (from nominal)	0.66, 0.36
EN4	PXIe-5172	Falling, edge Rising, edge	–20 (from nominal)	0.66, 0.36
$\overline{FAULT}$	PXIe-5172	Falling, edge	–20 (from nominal)	0.66, 0.36

Figure 6-1 shows a block diagram of the setup used for SEE testing of the TPS7H3014-SEP.

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 TPS7H3014-SEP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability was 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 exceeded the pre-defined 20% edge trigger, a data capture was initiated. 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. Neither, a single transient was capture by the oscilloscope measuring the outputs indicting the device is SET-free.

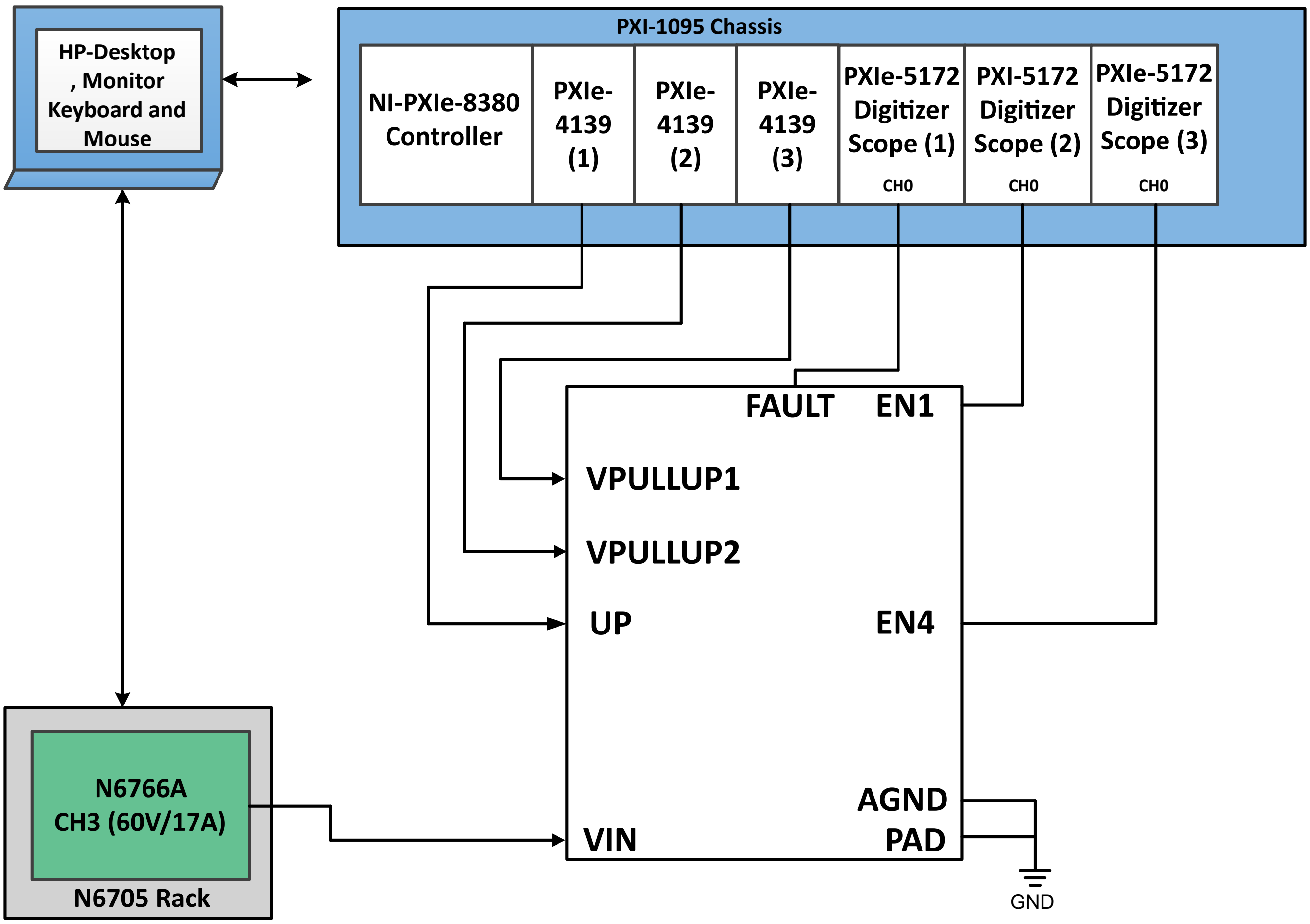


Figure 6-1. Block Diagram of the SEE Test Setup for the TPS7H3014-SEP

7 Destructive Single-Event Effects (DSEE)

7.1 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)]. The DUT temperature was monitored prior to being irradiated with a FLIR IR-camera to ensure the junction temperature. The species used for SEL testing was ^{109}Ag. Incident angle was used which achieved an LET_{EFF} of 48 MeV·cm^2/mg.

Three devices were tested under the loopback mode (for more details in loopback mode refer to footnote 1). In the loopback mode (used for DSEE) the overdrive voltage was selected to be 1V. This was done to avoid interpreting a transient as a functional interrupt. All devices were tested in the Waiting to Sequence DOWN *state*. Maximum recommend voltages were used for V_{IN}, V_{PULL_UPx} and V_{UP}. For more configuration information please refer to Table 6-1.

Not a single functional interrupt was observed, nor was there any high current event on any of the power supplies of the TPS7H3014-SEP. A total of three units were tested under the same conditions and configuration. This indicates the TPS7H3014-SEP is SEL-free. The results for three runs across three devices are shown in Table 7-1. A typical V_{IN} current versus time plot during a SEL run is shown in Figure 7-1.

Table 7-1. Summary of TPS7H3014-SEP SEL Test Condition and Results

RUN #	UNIT #	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg·s)	FLUENCE (ions·cm^2/mg)	SEL (NUMBER OF EVENTS)
1	1	^{109}Ag	48	1.18×10^5	1.00×10^7	0
2	2	^{109}Ag	48	1.21×10^5	1.00×10^7	0
3	3	^{109}Ag	48	1.43×10^5	1.00×10^7	0

Using the MFTF method described in *Single-Event Effects (SEE) Confidence Interval Calculations* application report and combining (or summing) the fluence of the four runs at 125°C (3×10^7), the upper-bound cross-section (using a 95% confidence level) is calculated as:

$\sigma_{SEL} \leq 1.23 \times 10^{-7}$cm^2/device for LET_{EFF} = 48 MeV·cm^2/mg and T = 125°C.

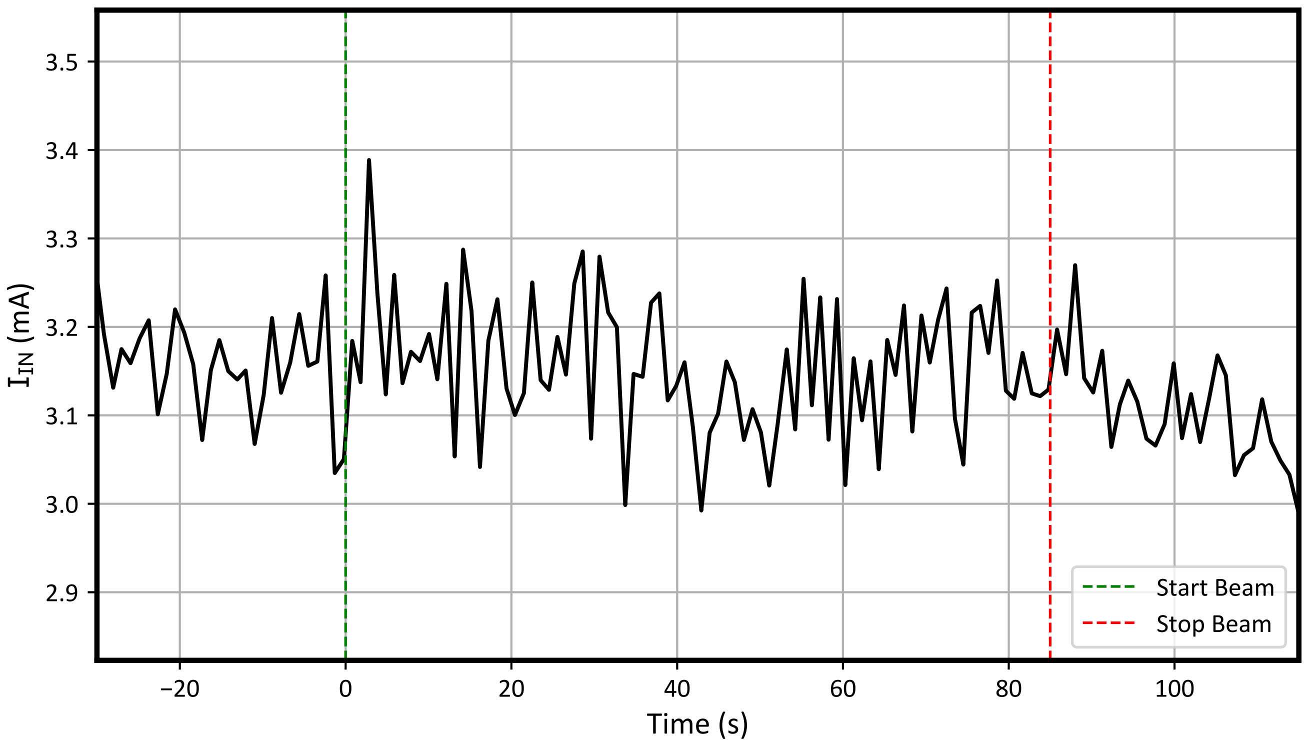


Figure 7-1. Current versus Time for I_{In}: Run #1 of the TPS7H3014-SEP at T = 125°C

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

During SEB/SEGR testing, the device was tested at room temperature. The same test conditions, in terms of biasing and voltage levels, apply for SEB/SEGR as was used during the SEL testing. In the case of the SEB/SEGR the device was tested in the following state machine states:

- Waiting to Sequence UP
  - All outputs are low (EN_X = LOW, SEQ_DONE = LOW, and PWRGD = LOW)
  - The device is waiting for a rising edge in UP to start the sequence up.
  - VUP = 0V (only difference from the SEL biasing)
- Waiting to Sequence DOWN
  - All outputs are high (EN_X = HIGH, SEQ_DONE = HIGH, and PWRGD = HIGH)
  - The device is waiting for a falling edge on DOWN to start a sequence down.

For more configuration information, please refer to Table 6-1.

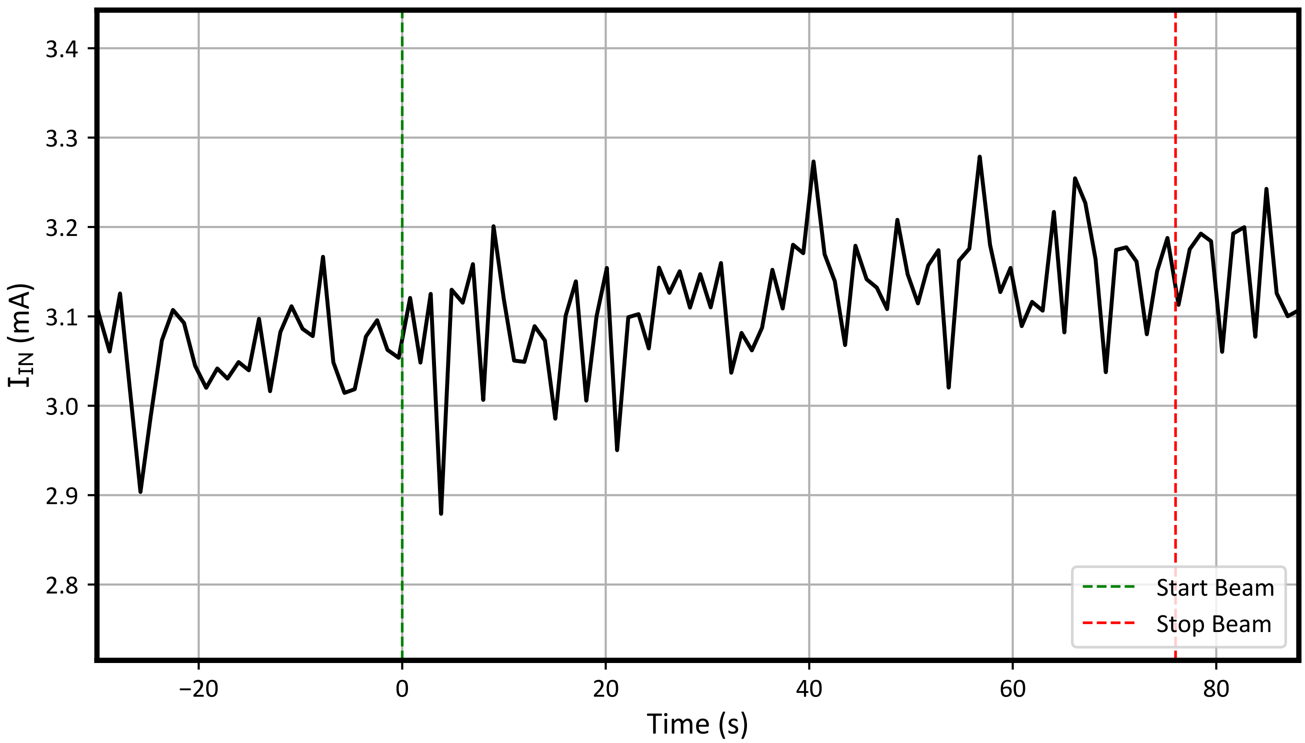
The results for six runs across three devices for SEB_X are shown in Table 7-2. During the testing of the 3 production devices and 6 SEB/SEGR runs, there were no SEB/SEGR events observed, indicating the TPS7H3014-SEP is SEB/SEGR free at 48MeV·cm^2/mg. Typical V_{IN} current vs time plots for SEB/SEGR on and off runs are shown in Figure 7-2 and Figure 7-3.

Table 7-2. Summary of TPS7H3014-SEP SEB/SEGR Test Condition and Results

RUN #	UNIT #	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg·s)	FLUENCE (ions·cm^2/mg)	ON/OFF STATUS	SEB EVENT?
4	1	^{109}Ag	48	9.92×10^4	1.00×10^7	On	No
5	1	^{109}Ag	48	1.23×10^5	1.00×10^7	Off	No
6	2	^{109}Ag	48	1.33×10^5	1.00×10^7	On	No
7	2	^{109}Ag	48	1.21×10^5	1.00×10^7	Off	No
8	3	^{109}Ag	48	1.39×10^5	1.00×10^7	On	No
9	3	^{109}Ag	48	1.45×10^5	1.00×10^7	Off	No

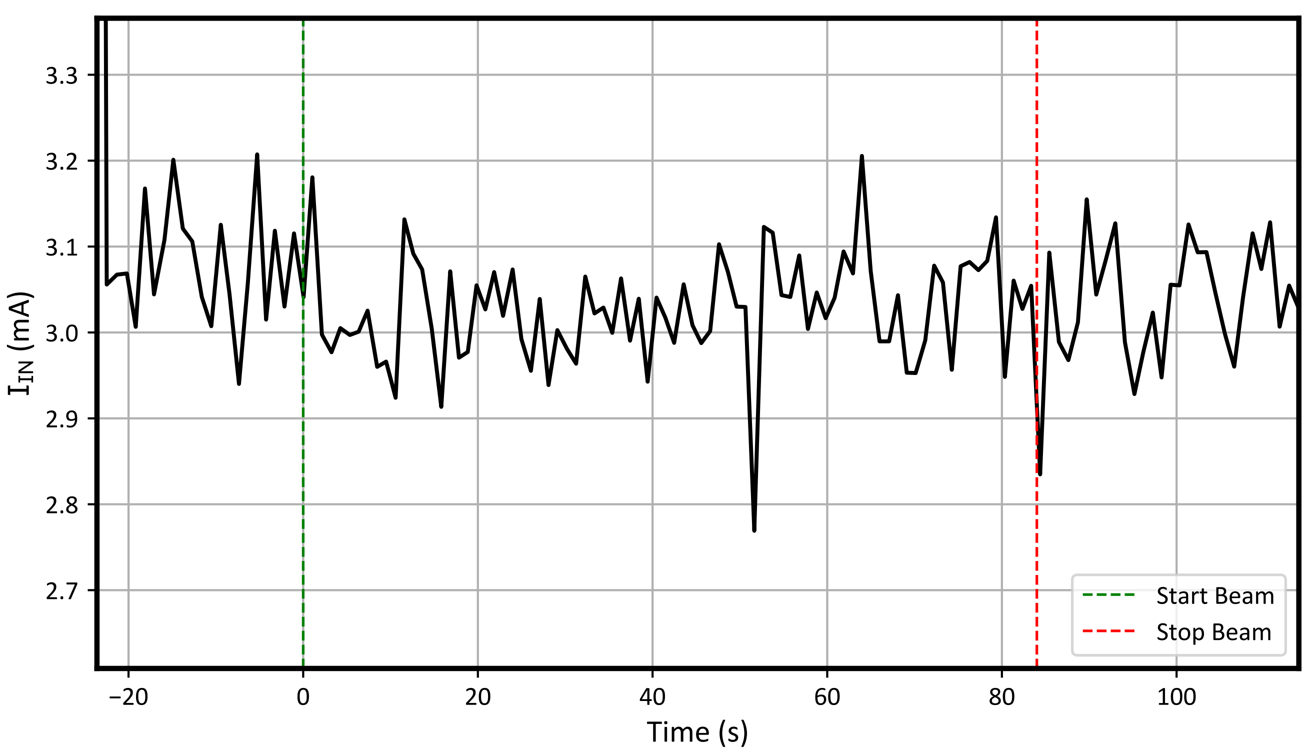
Using the MFTF method described in *Single-Event Effects (SEE) Confidence Interval Calculations* application report, the upper-bound cross-section (using a 95% confidence level) is calculated as:

$\sigma_{SEB} \leq 6.15 \times 10^{-8}$cm^2/device for LET_{EFF} = 48 MeV·cm^2/mg and T = 25°C.



On refers to the Waiting to Sequence $\overline{\text{DOWN}}$ state.

Figure 7-2. Current versus Time for I_{IN}: SEB On Run #4



Off refers to the Waiting to Sequence UP state.

Figure 7-3. Current versus Time for I_{IN}: SEB Off Run #5

8 Single-Event Transients (SET)

The primary focus of SETs were heavy-ion-induced transient upsets on EN1, EN4, or FAULT. SET testing was done at room temperature using ^{109}Ag heavy-ions which produced a LET_{EFF} of 48 MeV·cm^2/mg. The output signals were monitored by three NI PXIe-5172 scope cards. The PXIe-5172s were triggered with an edge-negative at –20% below the high voltage when in waiting to Sequence DOWN ***state.*** During the testing when the state machine was in the waiting to Sequence UP ***state*** , the trigger was set to 0.66V or 0.36V with an edge-positive trigger.

The PXIe-5172 sample rate was set to 100MS/s with a record length of 100k points (or samples). Two devices were tested under the loopback mode (for more details in loopback mode refer to footnote 1). In the loopback mode (used for SET) the overdrive voltage was selected to be ±20mV (typically). The device was tested under the following conditions.

1. Waiting to Sequence UP State (with –20mV).
2. Waiting to Sequence DOWN State (with+20mV).

The device was tested under a typical voltage for IN (5V) and $PULL\_UP_X$ (3.3V). Under these configurations not a single transient was recorded on EN1, EN4, or FAULT. This demonstrates the TPS7H3014-SEP is SET and SEFI free. The SET test conditions and results for three units are shown in Table 8-1.

Table 8-1. Summary of TPS7H3014-SP SET Test Condition and Results

RUN #	UNIT #	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions·cm^2/mg·s)	FLUENCE (ions·cm^2/mg)	WAITING TO SEQUENCE STATE	PXIe-5172 EN1 (# OF TRANSIENTS)	PXIe-5172 EN4 (# OF TRANSIENTS)	PXIe-5172 FAULT (# OF TRANSIENTS)
10	4	^{109}Ag	48	1.47×10^5	1.00×10^7	DOWN	0	0	0
11	4	^{109}Ag	48	1.48×10^5	1.00×10^7	UP	0	0	0
12	5	^{109}Ag	48	1.48×10^5	1.00×10^7	DOWN	0	0	0
13	5	^{109}Ag	48	1.50×10^5	1.00×10^7	UP	0	0	0

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 (2.54mm) 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 SEL, SEB/SEGR, and SET, the event rate calculation for the SEL, SEB/SEGR, and SET are shown in Table 9-1, Table 9-2, and Table 9-2, respectively. **It is important to note that this number is for reference since no SEL, SEB/SEGR, or SET 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)	48	4.50×10^{-4}	1.23×10^{-7}	5.54×10^{-11}	3.21×10^{-4}	4.95×10^{7}
GEO		1.48×10^{-3}		1.82×10^{-10}	2.31×10^{-3}	1.51×10^{7}

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)	48	4.50×10^{-4}	6.15×10^{-8}	2.77×10^{-11}	1.15×10^{-3}	9.90×10^{7}
GEO		1.48×10^{-3}		9.08×10^{-11}	3.78×10^{-3}	3.02×10^{7}

Table 9-3. SET (Waiting to Sequence DOWN) 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)	48	4.50×10^{-4}	1.84×10^{-7}	8.30×10^{-11}	3.46×10^{-3}	3.30×10^{7}
GEO		1.48×10^{-3}		2.72×10^{-10}	1.13×10^{-2}	1.01×10^{7}

Table 9-4. SET (Waiting to Sequence UP) 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)	48	4.50×10^{-4}	1.84×10^{-7}	8.30×10^{-11}	3.46×10^{-3}	3.30×10^{7}
GEO		1.48×10^{-3}		2.72×10^{-10}	1.13×10^{-2}	1.01×10^{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 TPS7H3014-SEP. Heavy-ions with LET_{EFF} = 48 MeV·cm^2/mg were used for the SEE characterization campaign. Flux of ≈10^5 ions/cm^2·s and fluences of ≈10^7 ions/cm^2 per run were used for the characterization. The SEE results demonstrated that the TPS7H3014-SEP is free of destructive SEL and SEB/SEGR. The device also shown to be SET and SEFI free at LET_{EFF} = 48 MeV·cm^2/mg and across the full electrical specifications. CREME96-based worst-week event-rate calculations for LEO (ISS) and GEO orbits for the DSEE and SET are presented for reference.

A References

1. M. Shoga and D. Binder, "Theory of Single Event Latchup in Complementary Metal-Oxide Semiconductor Integrated Circuits", *IEEE Trans. Nucl. Sci., Vol. 33(6)*, Dec. 1986, pp. 1714-1717.
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