Radiation Report

TPS7H60X5-SEP Single-Event Effects (SEE) Report

ABSTRACT

The purpose of this study is to characterize the single-event effects (SEE) performance due to heavy-ion irradiation of the TPS7H6005-SEP, TPS7H6015-SEP, and TPS7H6025-SEP. Heavy-ions with $\mathrm{LET_{EFF}}$ of 48 MeV × $\mathrm{cm^2/mg}$ was used to irradiate twelve production devices. Flux of approximately 10^5 $\mathrm{ions/cm^2{\times}s}$ and fluence of approximately 10^7 $\mathrm{ions/cm^2}$ per run were used for the characterization. The results demonstrate the performance of the TPS7H60x5-SEP under SEL and SEB and SEGR conditions at T = 125°C and T = 25°C, respectively. SET transients performance for output pulse width excursions ≥ |20%| from the nominal width and positive and negative edge transients on HO and LO are presented and discussed.

Table of Contents

List of Figures

List of Tables

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1 Introduction

The TPS7H60X5-SEP is a radiation-hardness-assured (RHA) Gallium Nitride (GaN) Field Effect Transistor (FET) gate driver designed for high frequency, high efficiency applications. The driver features:

- Absolute Maximum Voltage ratings
  - TPS7H6005-SEP: 200V
  - TPS7H6015-SEP: 60V
  - TPS7H6025-SEP: 22V
- Adjustable dead time (PWM mode)
- Approximately 30ns propagation delay
- Approximately 5.5ns high-side and low-side matching
- High-side and low-side 5V LDOs independent of supply voltage
- Two control input modes: Independent Input Mode (IIM) and PWM
  - IIM allows for outputs to be controlled by dedicated input
  - PWM allows for two complementary outputs signals to be generated from single input with resistor programmable dead-time

In IIM mode the user also has the ability to enable or disable the turn-on of both outputs when both inputs are on simultaneously (interlock protection). This gives the driver the ability to be used in multiple converter configurations.

The device is offered in a 56-pin plastic package. General device information and test conditions are listed in Table 1-1. For more detailed technical specifications, user guides, and application notes, see the TPS7H6005-SEP, the TPS7H6015-SEP, or the TPS7H6025-SEP product pages.

Table 1-1. Overview Information

Description(1)	Device Information
TI part number	TPS7H6005-SEP, TPS7H6015-SEP, TPS7H6025-SEP
Orderable number	TPS7H6005MDCATSEP, TPS7H6015MDCATSEP, TPS7H6025MDCATSEP
Device function	200, 60, or 22V half-bridge eGaN gate driver
Technology	LBC7 (Linear BiCMOS 7)
Exposure facility	Radiation Effects Facility, Facility for Rare Isotope Beams, Michigan State University (25 MeV/nucleon) & Cyclotron Facility, Texas A&M University (15 MeV/nucleon)
Heavy ion fluence per run	~1 × 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)

SEE testing was performed on an evaluation board designed for testing the TPS7H60x5-SEP under heavy-ion radiation. The board was powered up in different input and output conditions at Michigan State University (MSU) and Texas A&M University (TAMU) to cover the spectrum of destructive SEE (DSEE) and Single-Event Transients (SET). The devices were tested at two facilities, primarily the Facility for Rare Isotope Beams at MSU using a linear accelerator and the TAMU Cyclotron Radiation Effects Facility using a superconducting cyclotron and an advanced electron cyclotron resonance (ECR) ion source. DSEE testing included 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 TPS7H60x5-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 TPS7H60x5-SEP was tested for SEL at the maximum recommended input voltage (V_{IN}) of 14V and the maximum recommended boot voltage (V_{BOOT}) of 14V. The ASW (High-Side Driver Signal Return) was set to different voltages depending on variant. The TPS7H6005-SEP had ASW set to 150V, the TPS7H6015-SEP had ASW set to 45V, and the TPS7H6025-SEP had ASW set to 14V as these are the maximum recommended operating conditions for the devices. Three different operation modes were tested during SEL testing. The first mode was PWM mode with the EN (HI) and PWM (LI) inputs in the following configuration:

- EN/HI:
  - 14V DC signal (SEL)
- PWM/LI:
  - 14V square wave switching at 500kHz, 1MHz, and 2MHz (SEL)

The second and third modes of operation were IIM_{EN} (where the optional interlock protection is enabled) and IIM_{DIS} (where the optional interlock protection is disabled) mode (for the IIM modes there are static (IIM_{ST}) and switching (IIM_{SW}) cases) in which EN (HI) and PWM (LI) were configured in the following manner (both cases were tested under the same conditions):

- Case 1 - EN/HI = 0V, PWM/LI = 14V (Static SEL)
- Case 2 - EN/HI = 14V, PWM/LI = 0V (Static SEL)
- Case 3- EN/HI and PWM/LI = 14V square wave switching at 500kHz offset by 180° (Switching SEL)

During testing of the twelve devices, the TPS7H60x5-SEP did not exhibit any SEL with heavy-ions with LET_{EFF} = 50 MeV×cm^2/mg at flux of approximately 10^5 ions/cm^2 s, fluence of approximately 10^7 ions/cm^2, and a die temperature of 125°C.

The primary concern for SEB and SEGR was the power LDMOS of this device. Because of this, SEB/SEGR was evaluated up to the maximum V_{IN} and V_{BOOT} in both IIM and PWM mode. In IIM mode the TPS7H60x5-SEP was also tested in the “Off” case in which both EN/HI and PWM/LI = 0V to determine if either of the outputs incorrectly turned on when the outputs must not have during heavy-ion radiation. Because it has been shown that the MOSFET susceptibility to burnout decrements with temperature (5), the device was evaluated while operating under room temperatures. The specific test conditions the device was tested are as follows:

PWM Mode:

- EN/HI:
  - 14V DC signal (SEB_{ON})
  - 0V DC signal (SEB_{OFF})
- PWM/LI:
  - 14V Square Wave switching at 500kHz, 1MHz, and 2MHz (SEB_{ON})
  - 0V DC signal (SEB_{OFF})

IIM Modes:

- Case 1- EN/HI = 0V, PWM/LI = 14V (Static SEB_{ON})

- Case 2 - EN/HI = 14V, PWM/LI = 0V (Static SEB_{ON})
- Case 3 - EN/HI = 0V, PWM/LI = 0V (SEB_{OFF})
- Case 4 - EN/HI and PWM/LI = 14V square wave switching at 500kHz offset by 180° (Switching SEB_{ON})

During the SEB/SEGR testing, not a single input current event was observed, demonstrating that the TPS7H60x5-SEP is SEB/SEGR-free up to LET_{EFF} = 50.5 MeV×cm^2/mg at a flux of approximately 10^5 ions/cm^2×s, fluences of approximately 10^7 ions/cm^2, and a die temperature of ≈25°C.

The TPS7H60x5-SEP was characterized for SET with LET_{EFF} = 50.5 MeV×cm^2/mg at flux of approximately 10^5 ions/cm^2×s, fluence of approximately 10^7 ions/cm^2, and a die temperature of 25°C. For SET the device operated at nominal operating conditions with a V_{IN} of 12V and V_{BOOT} of 12V with ASW at the respective values. The specific test conditions for the devices for SET are as follows:

PWM Mode:

- EN/HI:
- 5V DC signal (SET)

PWM/LI:

- 5V Square Wave switching at 500kHz and 50% duty cycle (SET)

IIM Modes:

- Case 1 – EN/HI = 0V, PWM/LI = 5V (Static SET)
- Case 2 – EN/HI = 5V, PWM/LI = 0V (Static SET)
- Case 3 - EN/HI and PWM/LI = 5V square wave switching at 500kHz offset by 180° (Switching SET)

Under these conditions the device showed no SET signatures. To see the SET data and conditions of the TPS7H60x5-SEP, see Single-Event Transients (SET).

3 Device and Test Board Information

The TPS7H60x5-SEP is packaged in a 56-pin plastic package as shown in Figure 3-1. A TPS7H60x5-SEP evaluation board made specifically for radiation testing was used to evaluate the performance and characteristics of the TPS7H60x5-SEP under heavy ion radiation. The TPS7H60x5-SEP evaluation board is shown in Figure 3-2. The board schematic is shown in Figure 3-3.

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

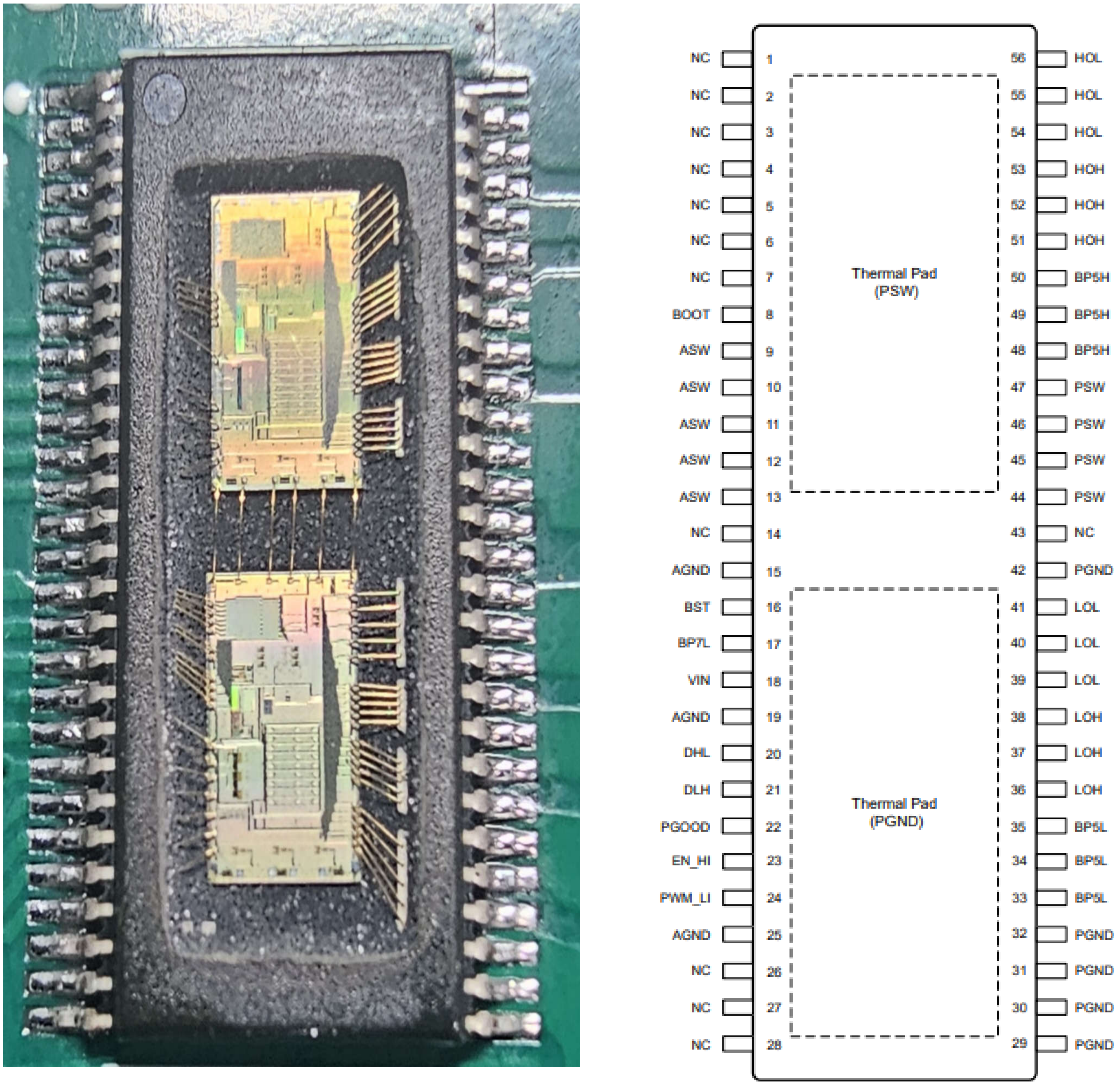


Figure 3-1. Photograph of Delidded TPS7H6005-SEP (Left) and Pinout Diagram (Right)

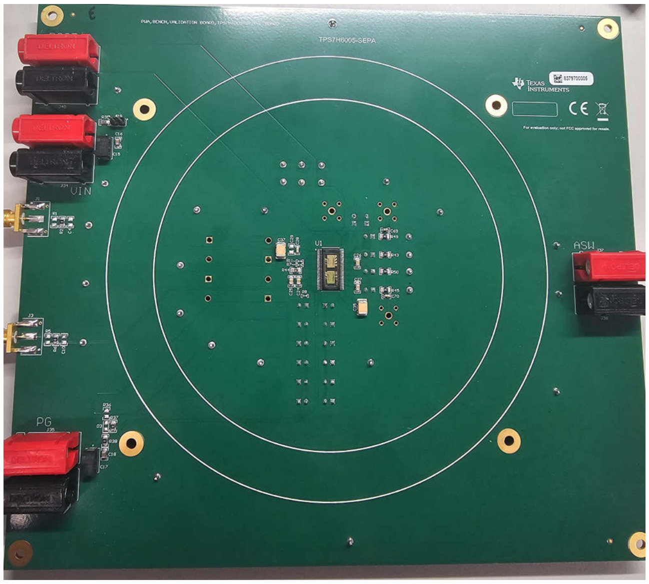


Figure 3-2. TPS7H60x5-SEP EVM Top View

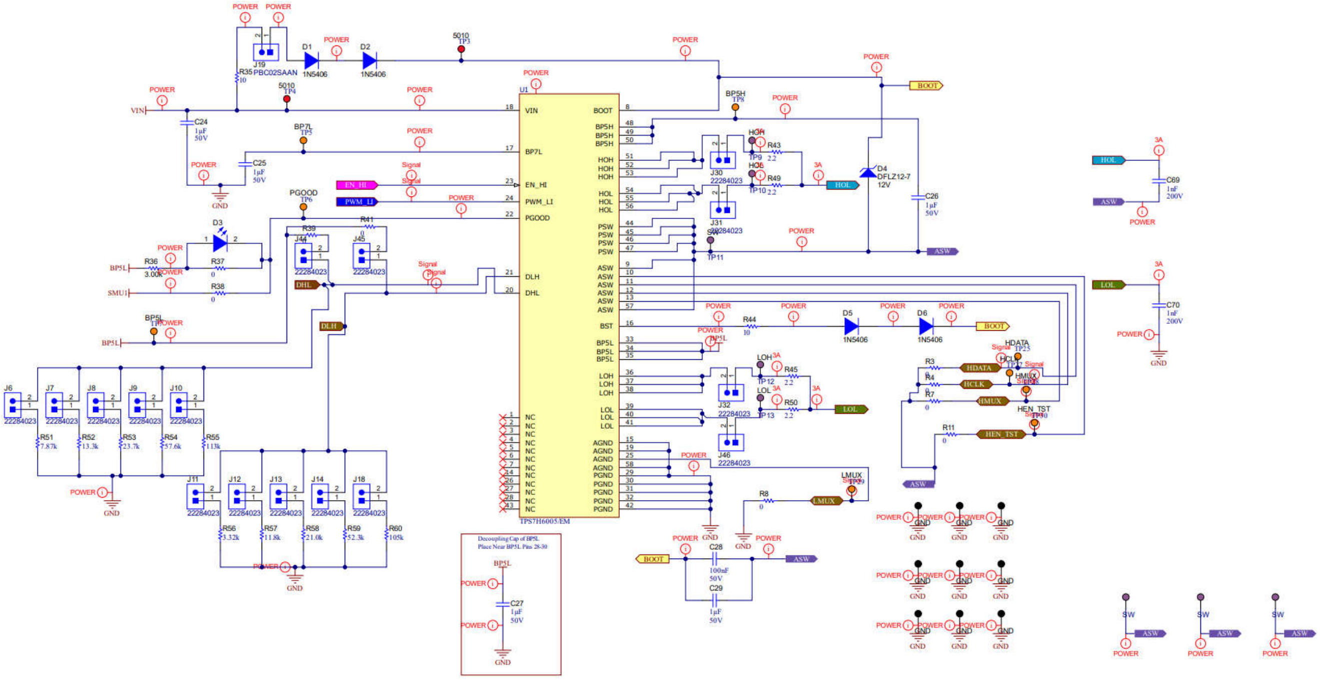


Figure 3-3. TPS7H60x5-SEP Evaluation Board Schematics

4 Irradiation Facility and Setup

The heavy-ion species used for the SEE studies on this product were provided and delivered by two facilities:

- Michigan State University (MSU) Facility for Rare Isotope Beams (FRIB) using a linear accelerator and an advanced electron cyclotron resonance (ECR) ion source. At the fluxes used, ion beams had good flux stability and high irradiation uniformity as the beam is collimated to a maximum of 20mm x 20mm^2 square cross-sectional area for the in-vacuum scintillator. Uniformity is achieved by scattering on a Cu foil and then performing magnetic defocusing. The flux of the beam is regulated over a broad range spanning several orders of magnitude. For these studies, ion flux of 8.36x10^4 to 1.14x10^5 ions/cm^2·s was used to provide heavy-ion fluences of 1.00 x 10^7 ions/cm^2.
- Texas A&M University (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 these studies, ion flux of 1.04x10^5 to 1.10x10^5 ions/cm^2·s was used to provide heavy-ion fluences of 1.00x10^7 ions/cm^2.

For the experiments conducted on this report, there were two ions used, ^{129}Xe and ^{109}Ag. ^{129}Xe was used to obtain LET$_{EFF}$ of 50.5 MeV × cm^2 / mg. ^{109}Ag was used to obtain LET$_{EFF}$ of 48 MeV × cm^2 / mg. The total kinetic energies for each of the ions were:

- ^{129}Xe = 3.225 GeV (25MeV / nucleon)
  - Ion uniformity for these experiments was 97.3%
- ^{109}Ag = 1.634 GeV (15 MeV/nucleon)
  - Ion uniformity for these experiments was between 91 and 92%

Figure 4-1 shows the TPS7H60x5-SEP Evaluation Board used for the data collection at both facilities. Although not visible in this photo, the beam port has a 1mil 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 70mm for all runs at MSU and 40mm for all runs at TAMU.

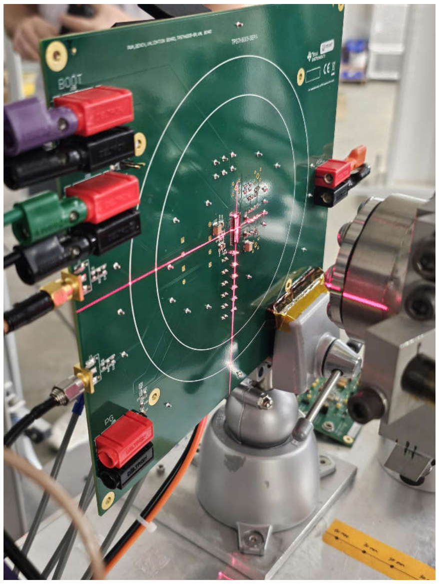
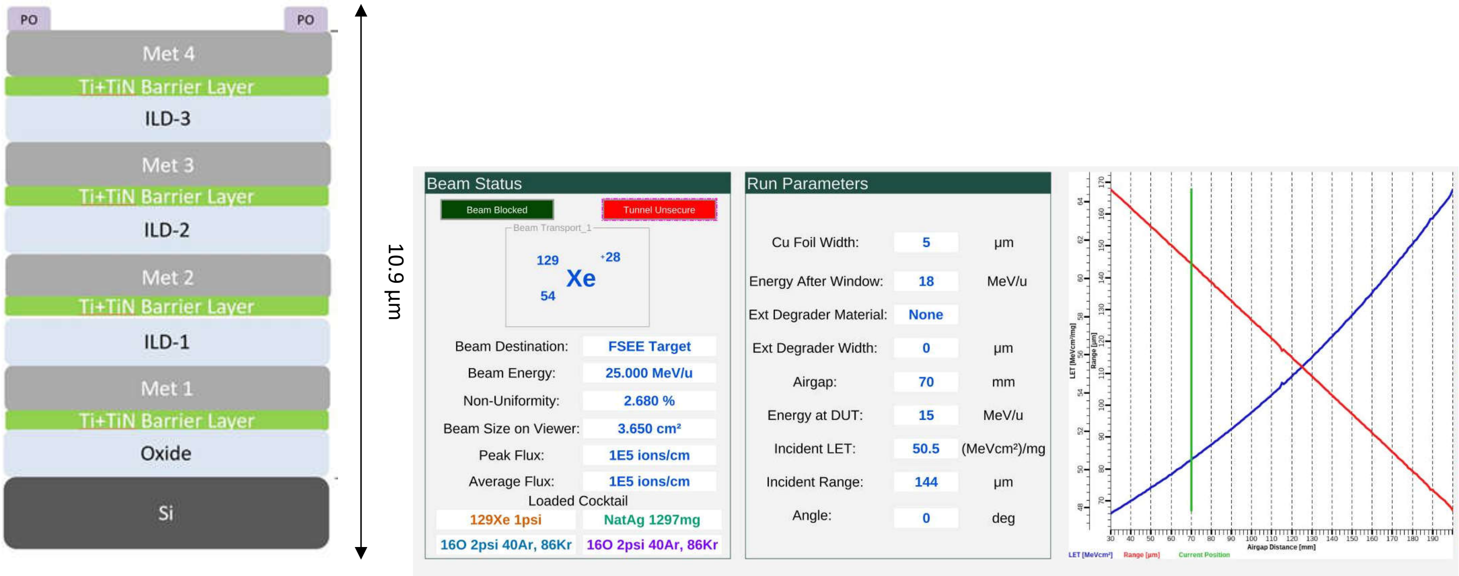


Figure 4-1. Photograph of the TPS7H60x5-SEP Evaluation Board in Front of the Heavy-Ion Beam Exit Port at the Michigan State FRIB

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



Beam Status

129 +28 Xe 54

Beam Destination: FSEE Target
Beam Energy: 25.000 MeV/u
Non-Uniformity: 2.680 %
Beam Size on Viewer: 3.650 cm²
Peak Flux: 1E5 ions/cm
Average Flux: 1E5 ions/cm

Loaded Cocktail

129Xe 1psi	NatAg 1297mg
16O 2psi 40Ar, 86Kr	16O 2psi 40Ar, 86Kr

Run Parameters

Cu Foil Width:	5	µm
Energy After Window:	18	MeV/u
Ext Degrader Material:	None	
Ext Degrader Width:	0	µm
Airgap:	70	mm
Energy at DUT:	15	MeV/u
Incident LET:	50.5	(MeVcm²)/mg
Incident Range:	144	µm
Angle:	0	deg

Figure 5-1. Generalized Cross-Section of the LBC7 Technology BEOL Stack on the TPS7H60X5-SEP (Left) and MSU Positioning Software Key Ion Parameters (Right)

The TPS7H60x5-SEP is fabricated in the TI Linear BiCMOS 250nm process with a 4LM back-end-of-line (BEOL) stack. The total stack height from the surface of the passivation to the silicon surface is 10.9µm based on nominal layer thickness as shown in Figure 5-1. Accounting for energy loss through the 1mil thick Aramica beam port window, the 70mm air gap, and the BEOL stack over the TPS7H60x5-SEP, the effective LET (LET$_{EFF}$) at the surface of the silicon substrate and the depth was determined with information provided by the MSU FRIB. The results are shown in Ion LET$_{EFF}$, Depth, and Range in Silicon.

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

Ion Type	Beam Energy (MeV / nucleon)	Angle of Incidence	Degrader Steps (Number)	Degrader Angle	Range in Silicon (µm)	LET$_{EFF}$ (MeV × cm^2/ mg)
^{109}Ag	15	0	0	0	95.1	48
^{129}Xe	25	0	0	0	144	50.5

6 Test Setup and Procedures

There were five input supplies used to power the TPS7H60x5-SP which provided V_{IN}, V_{BOOT}, EN/HI, PWM/LI, and ASW (ASW with respect to AGND). The VIN for the device was provided through channel 3 of an N6705C power module and ranged from 12V to 14V for SET and DSEE, respectively. The V_{BOOT} for the device was provided by Channel 1 of an N6705C power module and ranged from 12V to 14V SET and DSEE respectively. EN/HI and PWM/LI were provided by a National Instruments PXIe-5433 2-channel AWG or a National Instruments PXIe-4139 depending on the type of test. Lastly, the ASW was provided by a National Instruments PXIe-4137 and forced to 150V.

The primary signals monitored on the EVM were HO and LO and this was done so using two instruments. The first was a NI PXIe-5110 which triggered (based on HO) in two ways, pulse-width at 20% outside width in PWM or IIM_{SW} mode, and window (± 500mV with signal AC coupled) in IIM_{ST} mode. The second instrument was a MSO58B oscilloscope which triggered in a similar manner for the LO signal while also monitoring the BP5L signal.

All equipment other than the MSO58B 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 through an MXI controller and NI PXIe-8381 remote control module. The MSO58B was used using the manufacturer interface. The MSO was set to fast-frame for all SET data collection.

Table 6-1 lists the connections, limits, and compliance values used during the testing. Figure 6-1 shows a block diagram of the setup used for SEE testing of the TPS7H6003-SP.

Table 6-1. Equipment Settings and Parameters Used During the SEE Testing of the TPS7H60x5-SEP

Pin Name	Equipment Used	Capability	Compliance	Range of Values Used
V_{IN}	N6705C (CH # 3)	20.4V, 50A	5A	12 to 14V
V_{BOOT}	N6705C (CH # 1)	60V, 20A	5A	12 to 14V
ASW	PXIe-4137	200V, 1A	.5A	14 to 150V
EN/HI	PXIe-5433 (CH # 0)	$24V_{PK-PK}$, 80MHz	—	5V to 14V, 500kHz to 2MHz
	PXIe-4139	60V, 3A	3A	14V
PWM/LI	PXIe-5433 (CH # 1)	$24V_{PK-PK}$, 80MHz	—	5V to 14V, 500kHz to 2MHz
	PXIe-4139	60V, 3A	3A	14V
LO, BP5L	MSO58B	6.25GS / s	—	1GS / s
HO	PXIe-5110	100MS / s	—	100MS / s

All boards used for SEE testing were fully checked for functionality. Dry runs were also performed to maintain 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 TPS7H60x5-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 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.

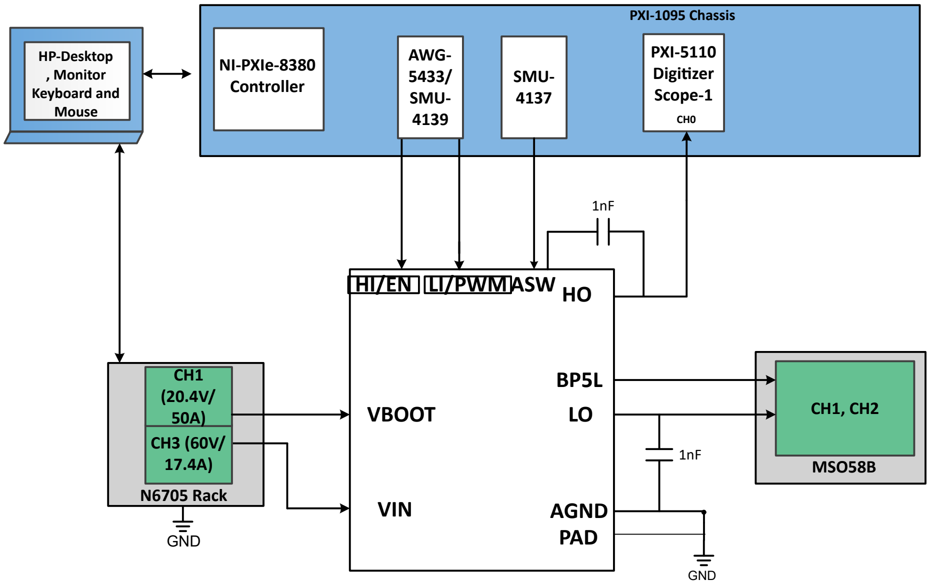


Figure 6-1. Block Diagram of the SEE Test Setup for the TPS7H60x5-SEP

7 Destructive Single-Event Effects (DSEE)

7.1 Single-Event Latch-up (SEL) Results

During the SEL testing the device was heated to 125°C by using a Closed-Loop PID controlled heat gun (MISTRAL 6 System (120V, 2400W) at TAMU or a cool-touch heat gun powered by a variac at MSU. The temperature of the die was verified using thermal camera prior to exposure to heavy ions.

The species used for the SEL testing was Xenon (^{129}Xe at 25MeV/nucleon) at MSU or Silver (^{109}Ag at 15MeV/nucleon) at TAMU. An angle of incidence of 0° was used to achieve an LET_{EFF} = 50.5MeV×cm^2/mg or 48MeV×cm^2/mg respectively (for more details, see Ion LET_{EFF}, Depth, and Range in Silicon). The kinetic energy in the vacuum for this ions is 3.225 GeV or 1.634GeV respectively. Flux of approximately 10^5 ions / cm^2×s and a fluence of approximately 10^7 ions/cm^2 per run was used. Run duration to achieve this fluence was approximately two minutes. The twelve devices were powered up and exposed to the heavy-ions using the maximum recommended input voltage and boot voltage of 14V. The ASW (High-Side Driver Signal Return) was set to 14, 45, or 150V with respect to AGND (low-side driver signal return) depending on the variant being tested. The device was set in both PWM and IIM modes during testing. For more information see Single-Event Effects section. No SEL events were observed during all fourteen runs, indicating that the TPS7H60x5-SEP is SEL-free up to 50.5MeV×cm^2/mg. Table 7-1 shows the SEL test conditions and results. Figure 7-1 shows a plot of the current versus time for run 1.

Table 7-1. Summary of TPS7H60x5-SEP SEL Test Condition and Results

Run Number	Unit Number	Variant	Ion	LET_{EFF} (MeV × cm^2 / mg)	Flux (ions × cm^2 / mg)	Fluence (Number of ions)	V_{IN}	V_{BOOT}	Mode	EN/HI	PWM/LI	SEL (# Events)
1	1	TPS7H6005	^{129}Xe	50.5	9.54×10^4	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 500kHz	0
2	1	TPS7H6005	^{129}Xe	50.5	8.80×10^4	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 1MHz	0
3	1	TPS7H6005	^{129}Xe	50.5	8.65×10^4	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 2MHz	0
4	2	TPS7H6005	^{129}Xe	50.5	1.02×10^5	1×10^7	14	14	IIM_{ENSW}	$14V_{pk\text{-}pk}$ 500kHz	$14V_{pk\text{-}pk}$ 500kHz	0
5	3	TPS7H6005	^{129}Xe	50.5	9.94×10^4	1×10^7	14	14	IIM_{DISSW}	$14V_{pk\text{-}pk}$ 500kHz	$14V_{pk\text{-}pk}$ 500kHz	0
6	4	TPS7H6015	^{129}Xe	50.5	1.1×10^5	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 500kHz	0
7	5	TPS7H6015	^{129}Xe	50.5	9.79×10^4	1×10^7	14	14	IIM_{ENSW}	$14V_{pk\text{-}pk}$ 500kHz	$14V_{pk\text{-}pk}$ 500 kHz	0
8	6	TPS7H6015	^{129}Xe	50.5	1×10^5	1×10^7	14	14	IIM_{DISSW}	$14V_{pk\text{-}pk}$ 500kHz	$14V_{pk\text{-}pk}$ 500kHz	0
9	7	TPS7H6025	^{129}Xe	50.5	1.02×10^5	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 500kHz	0
10	8	TPS7H6025	^{129}Xe	50.5	1.09×10^5	1×10^7	14	14	IIM_{ENSW}	$14V_{pk\text{-}pk}$ 500kHz	$14V_{pk\text{-}pk}$ 500kHz	0
11	9	TPS7H6005	^{109}Ag	48	1.04×10^5	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 500kHz	0
12	10	TPS7H6015	^{109}Ag	48	1.06×10^5	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 500kHz	0
13	11	TPS7H6025	^{109}Ag	48	1.06×10^5	1×10^7	14	14	PWM	$14V_{DC}$	$14V_{pk\text{-}pk}$ 500kHz	0
14	12	TPS7H6025	^{109}Ag	48	1.05×10^5	1×10^7	14	14	IIM_{DISSW}	$14V_{pk\text{-}pk}$ 500kHz	$14V_{pk\text{-}pk}$ 500kHz	0

Using the MFTF method shown in *Single-Event Effects (SEE) Confidence Interval Calculations* and combining (or summing) the fluences of the four runs at 125°C (14×10^7), the upper-bound cross-section (using a 95% confidence level) is calculated as:

$$\sigma_{SEL} \leq 2.63\, x\, 10^{-8}\, cm^2/device\ for\ LET_{EFF} = 50.5\, MeV \cdot cm^2/mg\ and\ T = 125°C \tag{1}$$

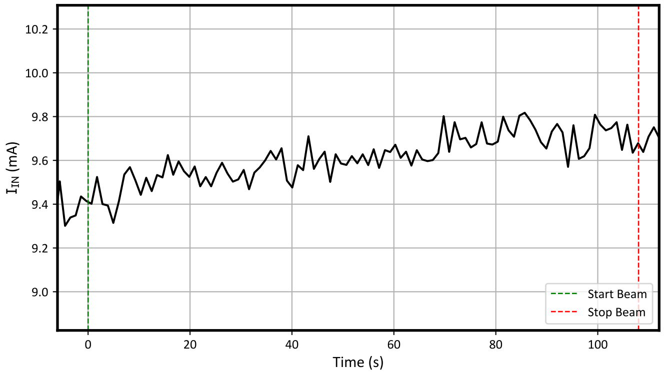


Figure 7-1. SEL Run 1 (PWM Mode, f_{sw} = 500kHz)

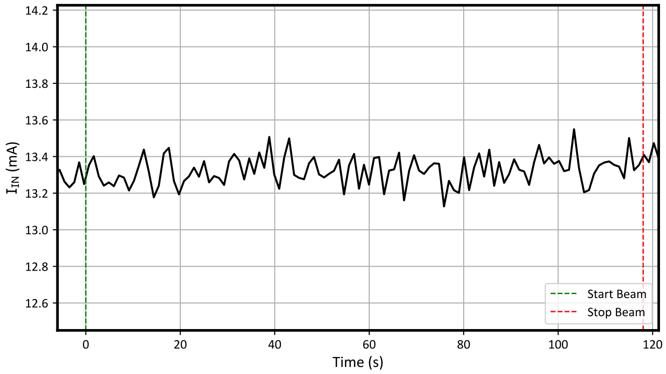


Figure 7-2. SEL Run 2 (PWM Mode, f_{sw} = 1MHz)

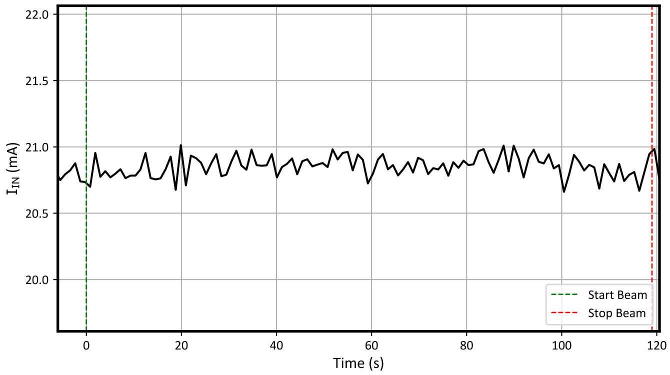


Figure 7-3. SEL Run 3 (PWM Mode, f_{sw} = 2MHz)

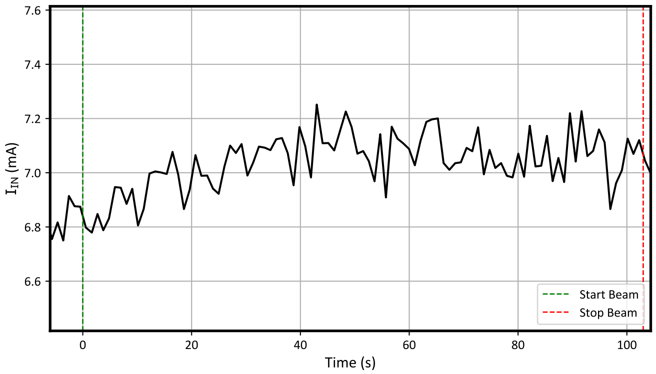


Figure 7-4. SEL Run 4 (IIM Enabled Mode, f_{SW} = 500kHz)

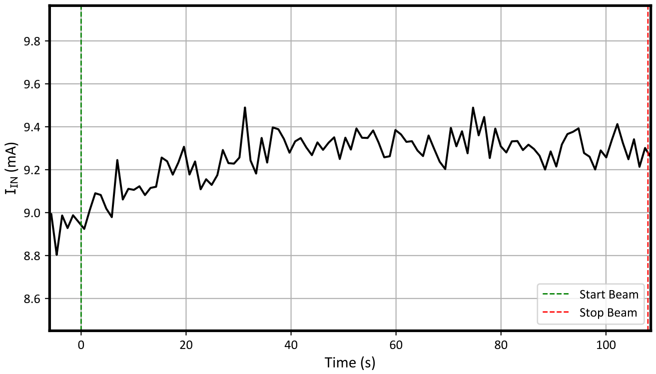


Figure 7-5. SEL Run 5 (IIM Disabled Mode, f_{SW} = 500kHz)

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

During the SEB/SEGR characterization, the device was tested at room temperature of approximately 25°C. The device was tested under both the enabled and disabled mode. For the SEB-OFF mode the device was disabled using the EN-pin by forcing 0V while in PWM mode and by holding both inputs low during the IIM mode testing. During the SEB/SEGR testing with the device enabled or disabled, not a single input current event was observed.

The species used for the SEB testing was Xenon (^{129}Xe at 25MeV/nucleon) at MSU or Silver (^{109}Ag at 15MeV/nucleon) at TAMU. An angle of incidence of 0° was used to achieve an LET_{EFF} = 50.5MeV×cm^2/mg or 48MeV×cm^2/mg respectively (for more details, see Ion LET_{EFF}, Depth, and Range in Silicon). The kinetic energy in the vacuum for this ions is 3.225Gev or 1.634GeV respectively. Flux of approximately 10^5 ions / cm^2×s and a fluence of approximately 10^7 ions/cm^2 per run was used. Run duration to achieve this fluence was approximately two minutes. The twelve devices (same as used in SEL testing) were powered up and exposed to the heavy-ions using the maximum recommended input voltage and boot voltage of 14V. The ASW (High-Side Driver Signal Return) was set to 14, 45 or 150 V depending on the variant being tested. The device was set in both PWM and IIM modes during testing. For more information, see Single-Event Effects section. No SEB/SEGR current events were observed during the twenty-six runs, indicating that the TPS7H60x5-SEP is SEB/SEGR-free up to LET_{EFF} = 50.5 MeV×cm^2/mg and across the full electrical specifications. Summary of TPS7H60x5-SEP SEB/SEGR Test Condition and Results shows the SEB/SEGR test conditions and results.

Table 7-2. Summary of TPS7H60x5-SEP SEB/SEGR Test Condition and Results

Run Number	Unit Number	Variant	Ion	LET_{EFF} (MeV × cm^2 / mg)	Flux (ions × cm^2/ mg)	Fluence (number of ions)	Enabled Status	V_{IN}	V_{BOOT}	Mode	Switching Frequency	SEB Event?
15	1	TPS7H6005	^{129}Xe	50.5	8.51×10^4	1×10^7	EN	14	14	PWM	500kHz	No
16	1	TPS7H6005	^{129}Xe	50.5	8.55×10^4	1×10^7	EN	14	14	PWM	1MHz	No
17	1	TPS7H6005	^{129}Xe	50.5	8.36×10^4	1×10^7	EN	14	14	PWM	2MHz	No
18	1	TPS7H6005	^{129}Xe	50.5	9.51×10^4	1×10^7	DIS	14	14	PWM	N/A	No
19	2	TPS7H6005	^{129}Xe	50.5	9.83×10^4	1×10^7	EN	14	14	IIM_{ENSW}	500kHz	No
20	2	TPS7H6005	^{129}Xe	50.5	8.5×10^4	1×10^7	EN	14	14	IIM_{ENST}	N/A	No
21	2	TPS7H6005	^{129}Xe	50.5	1.09×10^5	1×10^7	EN	14	14	IIM_{ENST}	N/A	No
22	2	TPS7H6005	^{129}Xe	50.5	1.08×10^5	1×10^7	DIS	14	14	IIM_{ENST}	N/A	No
23	3	TPS7H6005	^{129}Xe	50.5	1.07×10^5	1×10^7	EN	14	14	IIM_{DISSW}	500kHz	No
24	3	TPS7H6005	^{129}Xe	50.5	1.14×10^5	1×10^7	EN	14	14	IIM_{DISST}	N/A	No
25	3	TPS7H6005	^{129}Xe	50.5	1.11×10^5	1×10^7	EN	14	14	IIM_{DISST}	N/A	No
26	3	TPS7H6005	^{129}Xe	50.5	1.09×10^5	1×10^7	DIS	14	14	IIM_{DISST}	N/A	No
27	4	TPS7H6015	^{129}Xe	50.5	1.11×10^5	1×10^7	EN	14	14	PWM	500kHz	No
28	4	TPS7H6015	^{129}Xe	50.5	1.14×10^5	1×10^7	DIS	14	14	PWM	N/A	No
29	5	TPS7H6015	^{129}Xe	50.5	1.12×10^5	1×10^7	EN	14	14	IIM_{ENSW}	500kHz	No
30	6	TPS7H6015	^{129}Xe	50.5	9.93×10^4	1×10^7	EN	14	14	IIM_{DISSW}	500kHz	No

Table 7-2. Summary of TPS7H60x5-SEP SEB/SEGR Test Condition and Results (continued)

Run Number	Unit Number	Variant	Ion	LET_{EFF} (MeV × cm^2 / mg)	Flux (ions × cm^2/ mg)	Fluence (number of ions)	Enabled Status	V_{IN}	V_{BOOT}	Mode	Switching Frequency	SEB Event?
31	7	TPS7H6025	^{129}Xe	50.5	1×10^5	1×10^7	EN	14	14	PWM	500kHz	No
32	7	TPS7H6025	^{129}Xe	50.5	1.02×10^5	1×10^7	DIS	14	14	PWM	N/A	No
33	8	TPS7H6025	^{129}Xe	50.5	1.1×10^5	1×10^7	EN	14	14	IIM_{ENSW}	500kHz	No
34	9	TPS7H6005	^{109}Ag	48	1.04×10^5	1×10^7	EN	14	14	PWM	500kHz	No
35	9	TPS7H6005	^{109}Ag	48	1.1×10^5	1×10^7	DIS	14	14	PWM	N/A	No
36	10	TPS7H6015	^{109}Ag	48	1.05×10^5	1×10^7	EN	14	14	PWM	500kHz	No
37	10	TPS7H6015	^{109}Ag	48	1.08×10^5	1×10^7	DIS	14	14	PWM	N/A	No
38	11	TPS7H6025	^{109}Ag	48	1.05×10^5	1×10^7	EN	14	14	PWM	500kHz	No
39	11	TPS7H6025	^{109}Ag	48	1.06×10^5	1×10^7	DIS	14	14	PWM	N/A	No
40	12	TPS7H6025	^{109}Ag	48	1.07×10^5	1×10^7	EN	14	14	IIM_{DISSW}	500kHz	No

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

$$\sigma_{SEB} \leq 1.42 \, x \, 10^{-8} \, cm^2/device \; for \; LET_{EFF} = 50.5 \, MeV \cdot cm^2/mg \; and \; T = 25°C \tag{2}$$

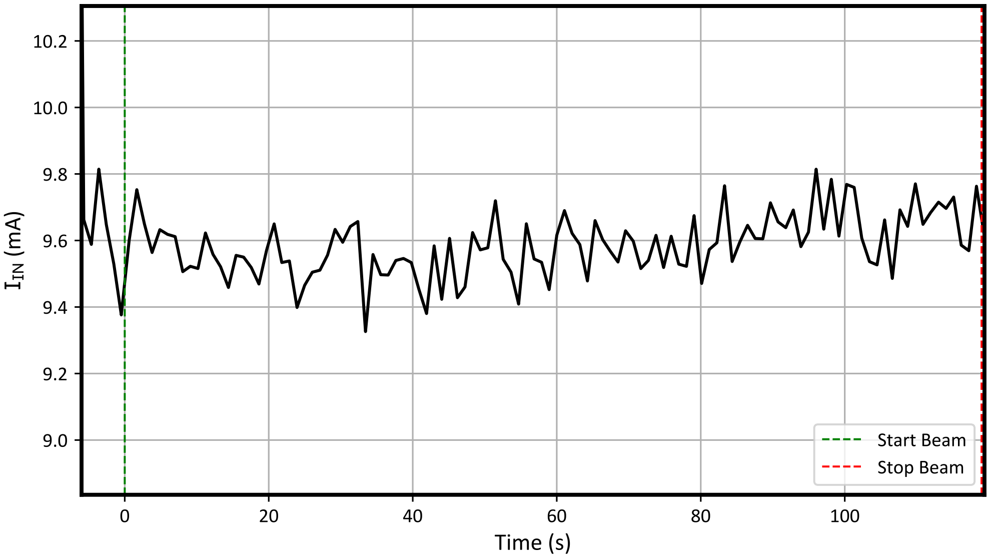


Figure 7-6. SEB On Run 15 (PWM Mode, f_{sw}= 500kHz)

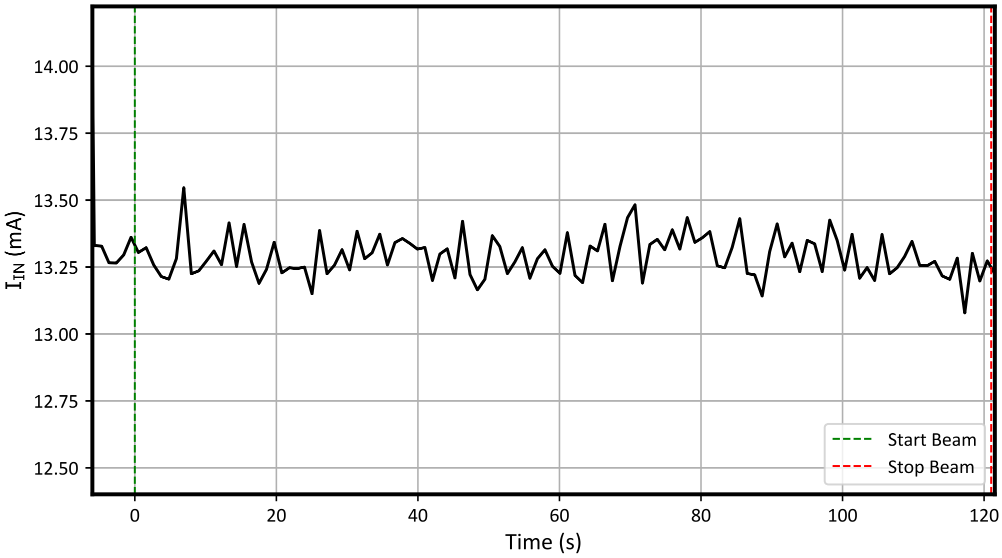


Figure 7-7. SEB On Run 16 (PWM Mode, f_{sw} = 1MHz)

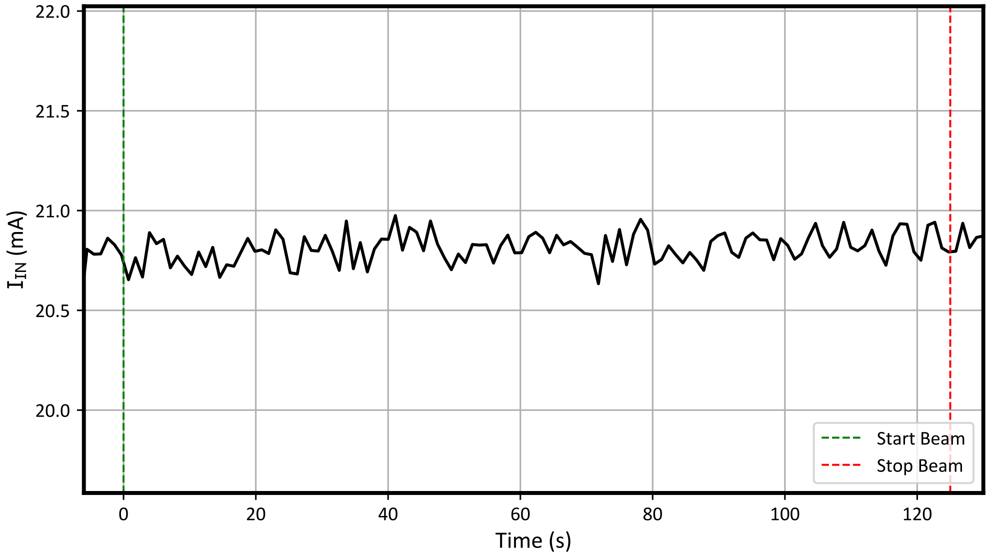


Figure 7-8. SEB On Run 17 (PWM Mode, f_{sw}= 2MHz)

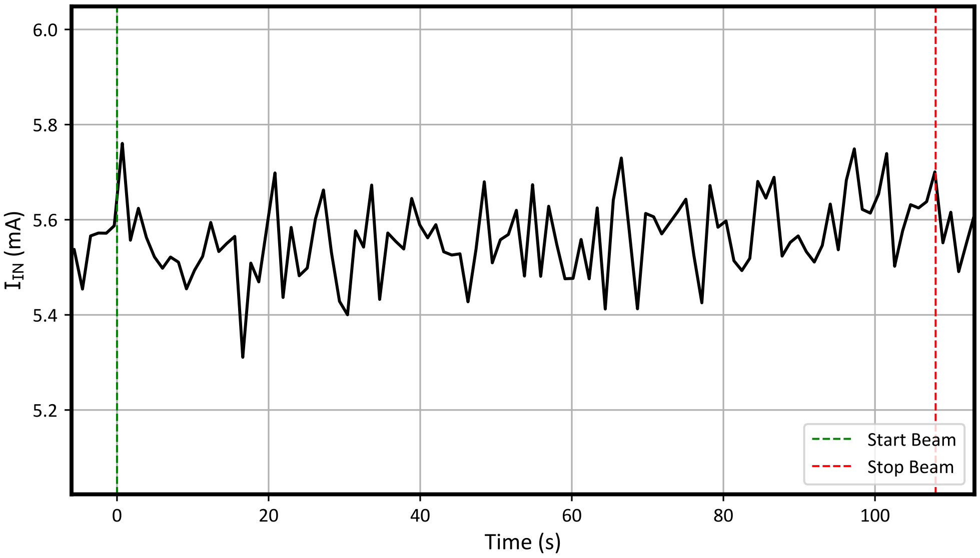


Figure 7-9. SEB Off Run 18 (PWM Mode)

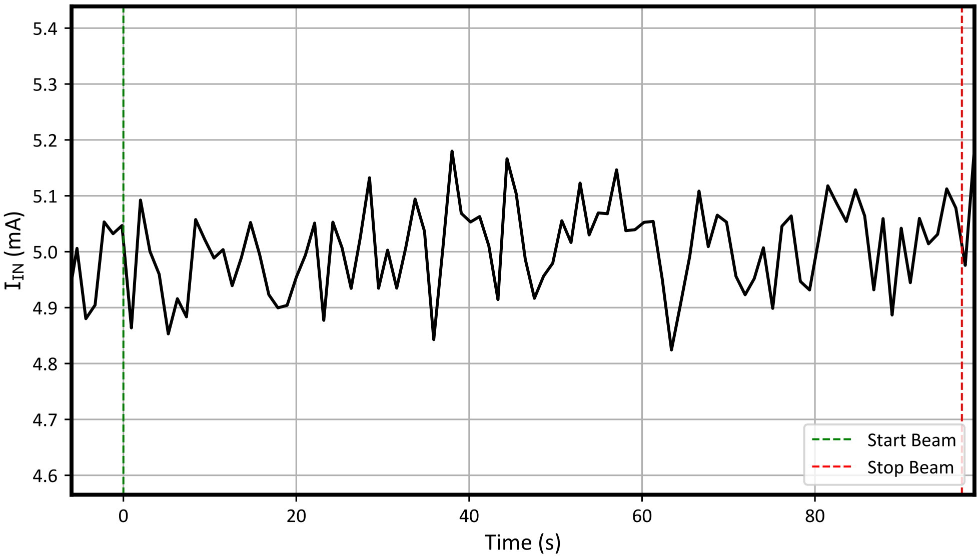


Figure 7-10. SEB On Run 20 (IIM-Enabled Mode, EN/HI = 14V)

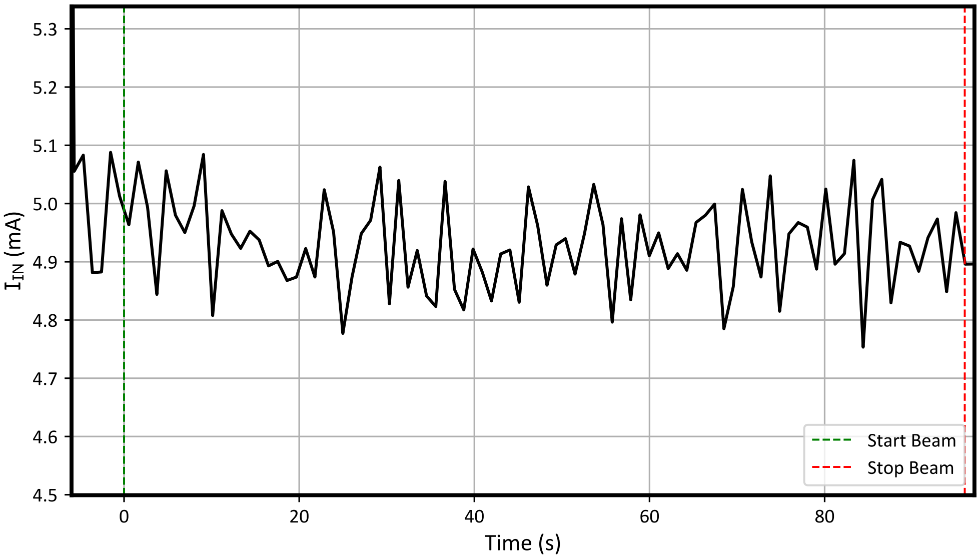


Figure 7-11. SEB Off Run 22 (IIM-Enabled Mode)

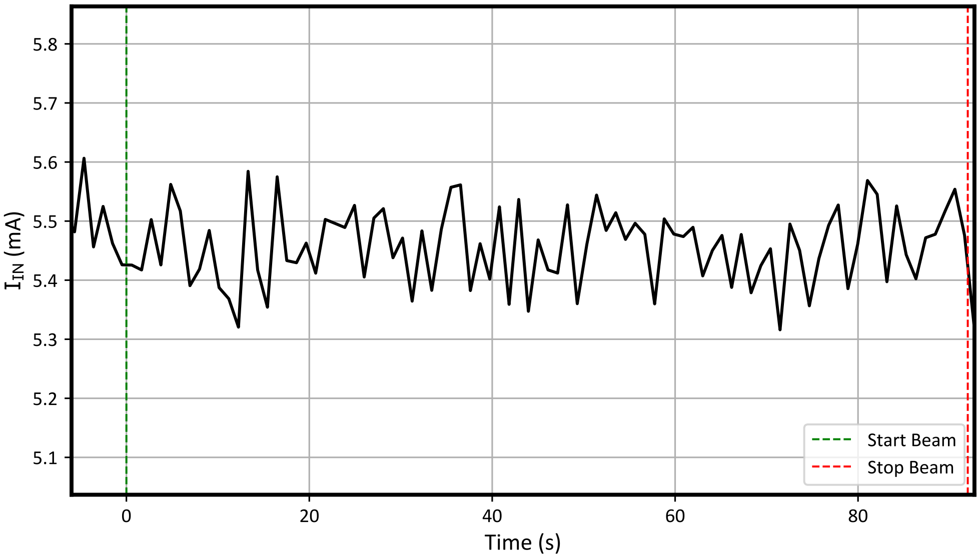


Figure 7-12. SEB On Run 24 (IIM-Disabled Mode, PWM/LI = 14V)

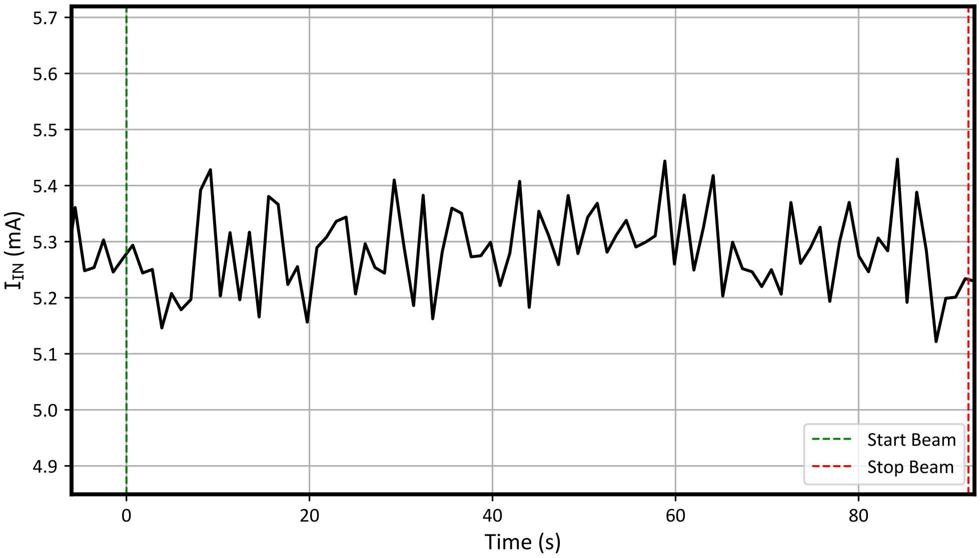


Figure 7-13. SEB Off Run 26 (IIM-Disabled Mode)

8 Single-Event Transients (SET)

The primary focus of SETs were heavy-ion-induced transient upsets on the output signals HO and LO (with a 1nF capacitive load on the outputs as seen in block diagram). SET testing was done at room temperature across two ion species, ^{109}Ag (TAMU) and ^{129}Xe (MSU) which produced a range of LET_{EFF} of 48 to 50.5MeV×cm^2/mg for more details, see Ion LET_{EFF}, Depth, and Range in Silicon. HO and LO were monitored by two different scopes, a NI PXIe-5110 and a MSO58B oscilloscope. During PWM and IIM_{SW} mode testing, each scope was configured to trigger based on an *outside* pulse width measurement, where the window for the output signal was 20% (±200ns). During the IIM_{ST} modes, the same two scopes were used, however, the trigger was a window which was 500mV above or 500mV below 0V with the signals AC-coupled. The signals in this mode were monitored to see if the signal ever went low when the signal was supposed to have been high, or high when supposed to have been low. During all SET testing, there was no cross-conduction in either PWM or IIM mode. For all SET testing no SET/SEFI events were observed during the twelve runs, indicating that the TPS7H60x5-SEP is SET/SEFI-free up to LET_{EFF} = 50.5 MeV×cm^2/mg and across the full electrical specifications. During all SET/SEFI testing there were no overshoot events observed indicating that the TPS7H60x5-SEP is also overshoot free up to LET_{EFF} = 50.5 MeV×cm^2/mg and across the full electrical specifications.

Waveform size, sample rate, trigger type, value, and signal for all scopes used is listed in Table 8-1.

Table 8-1. Scope Settings

Scope Model	Trigger Signal	Trigger Type	Trigger Value	Record Length	Sample Rate
MSO58B	LO	Pulse Width and Window	± 20% / ±500mV	20µs / div	250MS / s
	BP5L	N/A	N/A		
PXIe-5110	HO	Pulse Width and Window	± 20% / ±500mV	20k	100MS / s

Table 8-2. Summary of TPS7H60x5-SEP SET Test Condition and Results

Run Number	Unit Number	Variant	Ion	LET_{EFF} (MeV × cm^2 / mg)	Flux (ions × cm^2/ mg)	Fluence (number of ions)	Mode	MSO58B LO Number	PXIe-5110 HO Number
41	1	TPS7H6005	^{129}Xe	50.5	9.49×10^4	1×10^7	PWM	0	0
42	2	TPS7H6005	^{129}Xe	50.5	1.04×10^5	1×10^7	IIM_{ENSW}	0	0
43	3	TPS7H6005	^{129}Xe	50.5	1.13×10^5	1×10^7	IIM_{DISSW}	0	0
44	4	TPS7H6015	^{129}Xe	50.5	1.13×10^5	1×10^7	PWM	0	0
45	5	TPS7H6015	^{129}Xe	50.5	9.44×10^4	1×10^7	IIM_{ENSW}	0	0
46	6	TPS7H6015	^{129}Xe	50.5	1×10^5	1×10^7	IIM_{DISSW}	0	0
47	7	TPS7H6025	^{129}Xe	50.5	1.02×10^5	1×10^7	PWM	0	0
48	8	TPS7H6025	^{129}Xe	50.5	1.03×10^5	1×10^7	IIM_{ENSW}	0	0
49	9	TPS7H6005	^{109}Ag	48	1.08×10^5	1×10^7	PWM	0	0
50	10	TPS7H6015	^{109}Ag	48	1.07×10^5	1×10^7	PWM	0	0
51	11	TPS7H6025	^{109}Ag	48	1.05×10^5	1×10^7	PWM	0	0
52	12	TPS7H6025	^{109}Ag	48	1.06×10^5	1×10^7	IIM_{DISSW}	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 shown in *Heavy Ion Orbital Environment Single-Event Effects Estimations*. Assume a minimum shielding configuration of 100mils (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 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. Note that this number is for reference since no SEL or SEB/SEGR events were observed. SET orbit rate for the TPS7H60X5-SEP device is listed in SEB/SEGR Event Rate Calculations for Worst-Week LEO and GEO Orbits. As no SET events were observed, the numbers provided are for reference.

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)	50.5	3.80×10^{-4}	2.63×10^{-8}	1.00×10^{-11}	4.17×10^{-4}	2.74×10^{8}
GEO		1.23×10^{-3}		3.24×10^{-11}	1.35×10^{-3}	8.45×10^{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)	50.5	3.80×10^{-4}	1.42×10^{-8}	5.39×10^{-12}	2.24×10^{-4}	5.09×10^{8}
GEO		1.23×10^{-3}		1.75×10^{-11}	7.27×10^{-4}	1.57×10^{8}

Table 9-3. SET 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)	50.5	3.80×10^{-4}	3.07×10^{-8}	1.17×10^{-11}	4.86×10^{-4}	2.35×10^{8}
GEO		1.23×10^{-3}		3.78×10^{-11}	1.58×10^{-3}	7.24×10^{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 TPS7H60x5-SEP 200V half-bridge eGaN gate driver. Heavy-ions with LET_{EFF} = 48 to 50.5 MeV×cm^2/mg were used for the SEE characterization campaign. Flux of approximately 10^5 ions / cm^2 × s and fluences of approximately 10^7 ions / cm^2 per run were used for the characterization. The SEE results demonstrated that the TPS7H60x5-SEP is free of destructive SEL, SEB/SEGR, and SET/SEFI free at LET_{EFF} = 50.5 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.

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