Radiation Report

Single-Event Effects (SEE) Radiation Report of the TPS7H502X-SP

ABSTRACT

The purpose of this study is to characterize the single-event effects (SEE) performance due to heavy-ion irradiation of the TPS7H502X-SP. Heavy-ions with LET_{EFF} of 75MeV·cm^2 /mg were used to irradiate 8 production devices and 13 pre-production devices. Flux of 4×10^4 to 1×10^5 ions×cm^2/s and fluence of ≈10^7 ions/cm^2 per run were used for the characterization. The results demonstrated that the TPS7H502X-SP is SEL-free up to 75MeV·cm^2/mg at T = 125°C and SEB/SEGR free up to 75MeV·cm^2/mg at T = 25°C. SET transients performance for output pulse-width excursions ≥ |20%| from the nominal pulse-width in an open-loop configuration are discussed. SET transient performance for output voltage excursions ≥ |3%| and switch pulse-width excursions ≥ |20%| are also discussed with the device in a flyback configuration.

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1 Introduction

The TPS7H502X-SP is a radiation-hardness-assured, current mode, single-ended PWM controller with an integrated gate driver that can be utilized in both silicon and gallium nitride (GaN) power semiconductor based converter designs. The TPS7H502X-SP integrates several key functions such as:

- Soft-start, enable, and adjustable slope compensation
- 0.6V ±1% voltage reference tolerance
- Internal oscillator through the RT pin or external frequency control through the SYNC pin
- Switching frequencies up to 1MHz
- Input voltage range from 4.5V to 14V
- Programmable VLDO voltage (4.5V to 5.5V) that can be connected directly to driver stage input (PVIN) for operation with GaN FETs

The TPS7H5020 has a maximum duty cycle of 100% while the TPS7H5021 has a maximum duty cycle of 50%. The controller supports numerous power converter topologies, including flyback, forward, and boost.

The device is offered in a 24-pin plastic package. General device information and test conditions are listed in the overview information table. For more detailed technical specifications, user-guides, and application notes please go to device product page.

Table 1-1. Overview Information

DESCRIPTION(1)	DEVICE INFORMATION
TI Part Number	TPS7H502X-SP
Orderable Part Number	5962R2420101PYE (TPS7H5020-SP) or 5962R420102PYE (TPS7H5021-SP)
Device Function	PWM Controller with Integrated Gate Driver
Technology	LBC7 (Linear BiCMOS 7)
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University (15 MeV/nucleon) and Facility for Rare Istotope Beams, K500 Cyclotron (KSEE), Michigan State University (19.5MeV/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 TPS7H502X-SP 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 TPS7H502X-SP , 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 TPS7H502X-SP was tested for SEL at the maximum recommended operating conditions of Vin=PVIN=14V and VLDO=5.5V for the silicon mode and Vin=14V and PVIN=VLDO=5.5V for the GaN mode. During testing of the 6 production and 7 pre-production devices, the TPS7H502X-SP did not exhibit any SEL with heavy-ions with LET_{EFF} = 75MeV·cm^2 /mg at flux ≈10^5 ions×cm^2/s , fluence of ≈10^7 ions/cm^2, and a die temperature of 125°C.

The TPS7H502X-SP was evaluated for SEB/SEGR at a maximum voltage of 14V in the enabled and disabled mode. 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. The TPS7H502X-SP was tested for SEB at the maximum recommended operating conditions of V_{IN}=P_{VIN}=14V and V_{LDO}=5.5V for the silicon mode and V_{IN}=14V and P_{VIN}=V_{LDO}=5.5V for the GaN mode. The device was also tested for SEB Off by disabling the device. During the SEB/SEGR testing, not a single current event was observed, demonstrating that the TPS7H502X-SP is SEB/SEGR-free up to LET_{EFF} = 75MeV·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 TPS7H502X-SP was characterized for SET at flux of ≈5 × 10^4 to 1 × 10^5 ions×cm^2/s , fluences of 10^7 ions/cm^2, and room temperature. The device was characterized at V_{IN} of 12V for the silicon mode and 5V for the GaN mode. Heavy-ions with LET_{EFF} of 75MeV·cm^2/mg were used to characterize the transient performance. To see the SET results of the TPS7H502X-SP, please refer to Single-Event Transients (SET).

3 Device and Test Board Information

The TPS7H502X-SP is packaged in a *24*-pin HTSSOP PWP plastic package as shown in Figure 3-1. A custom TPS7H502X-SP evaluation module, designed for open-loop SEE testing and the TPS7H5020FLYEVM-CVAL, used for flyback SEE testing, were used to evaluate the performance and characteristics of the TPS7H502X-SP under heavy ion radiation. The evaluation modules are shown in Figure 3-2 and . The schematics are shown in Figure 3-3.

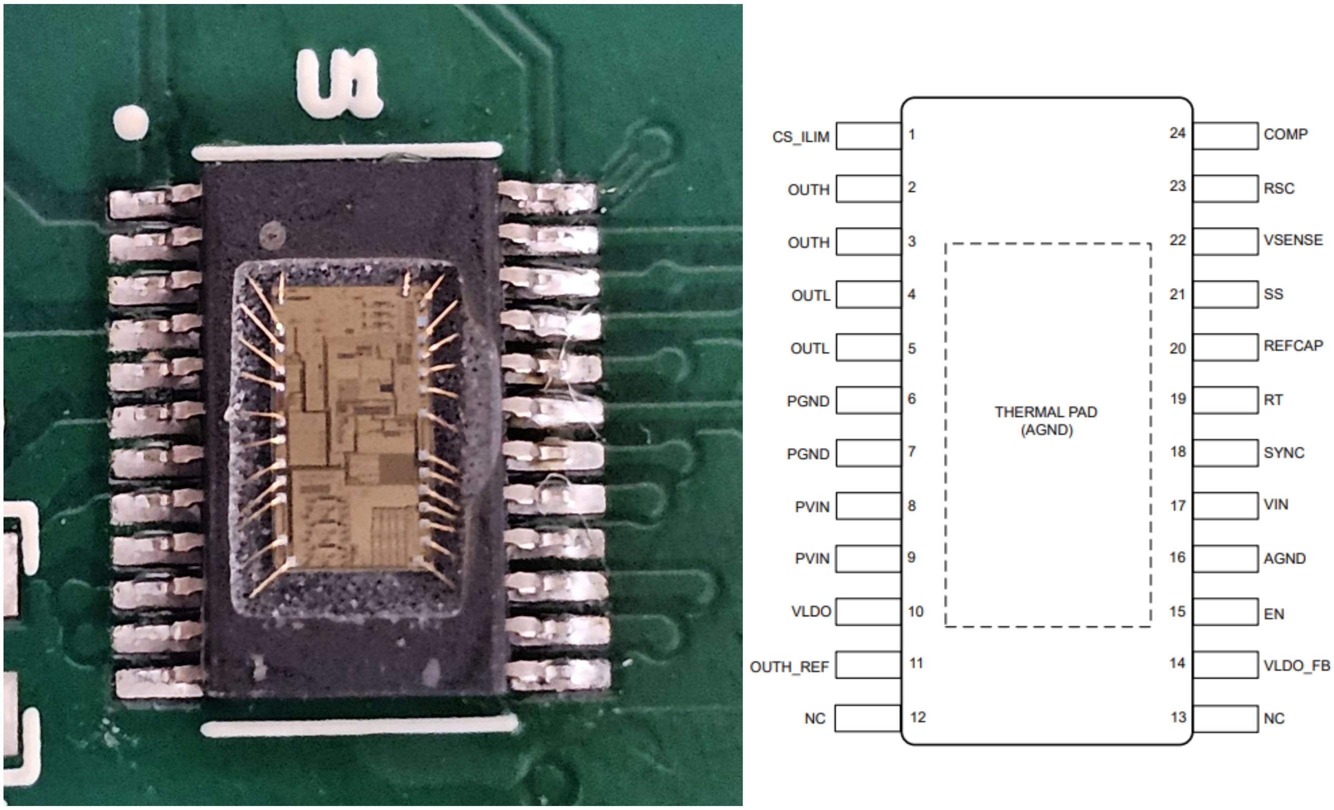


Figure 3-1. Photograph of Delidded TPS7H502X-SP [Left] and Pinout Diagram [Right]

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

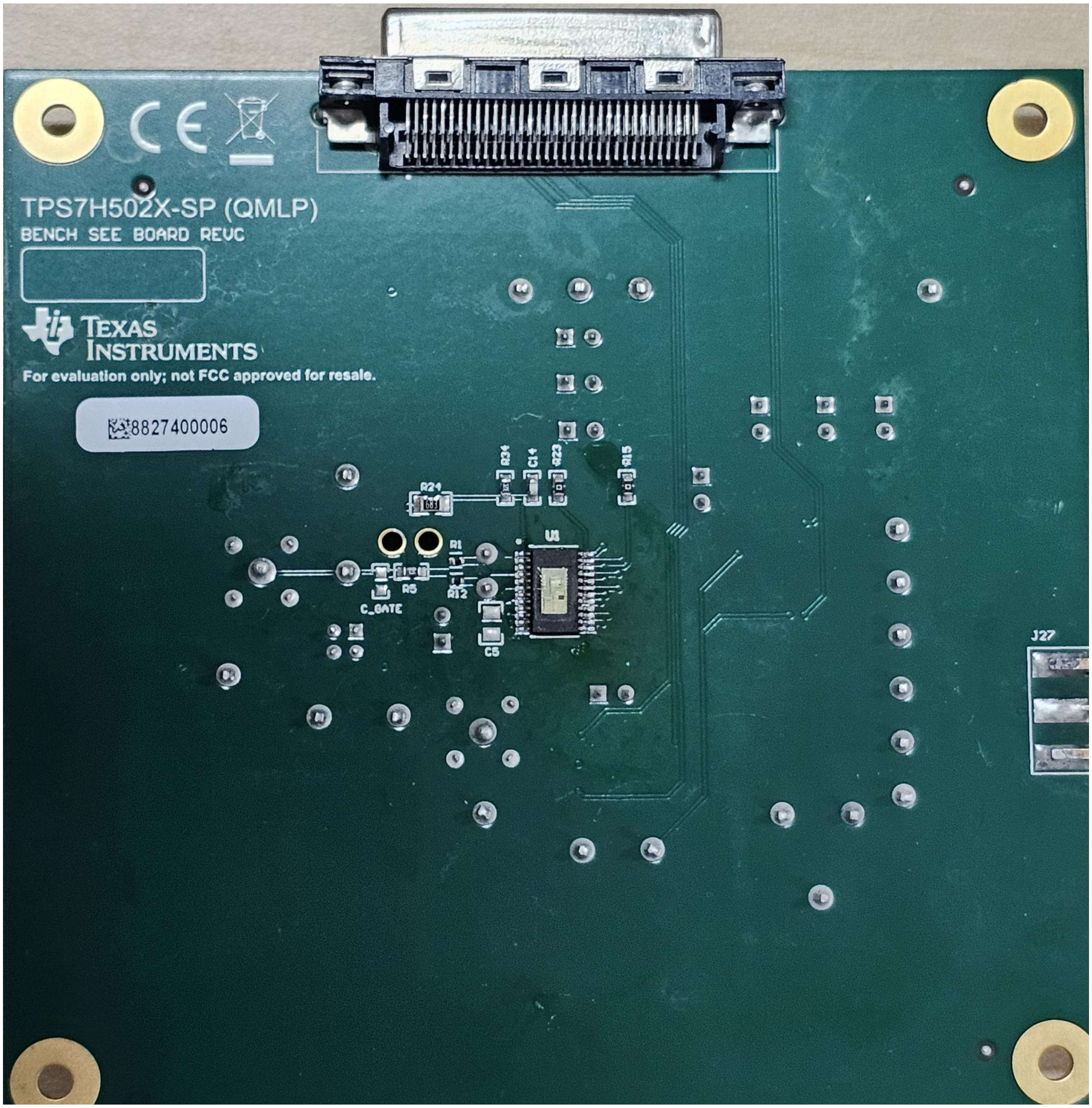


Figure 3-2. TPS7H502X-SP Custom EVM Top View

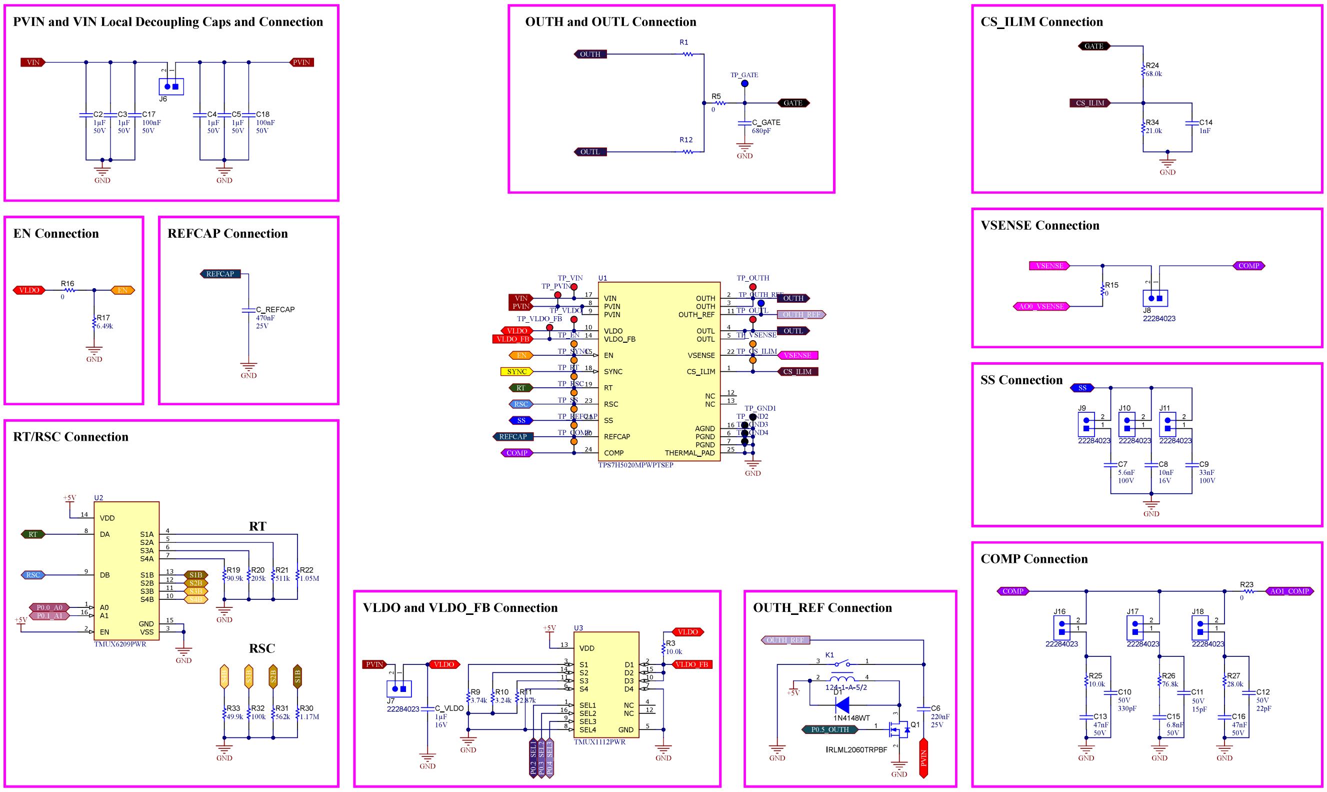


Figure 3-3. TPS7H502X-SP Custom EVM Controller Schematic

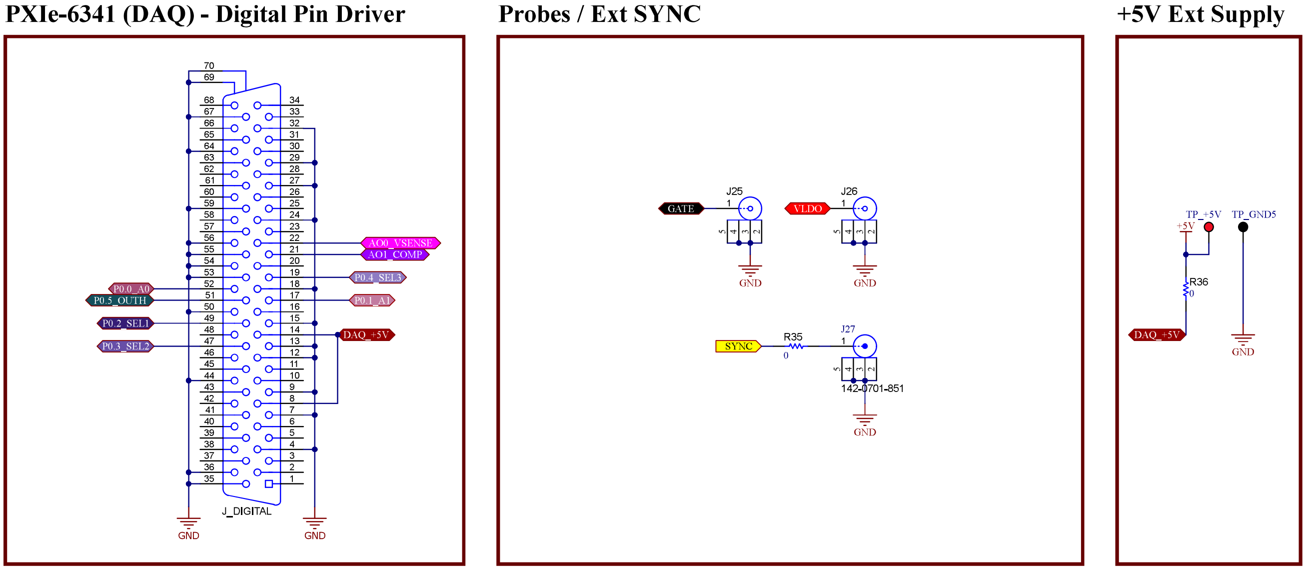


Figure 3-4. TPS7H502X-SP Custom EVM Auxiliary Schematic

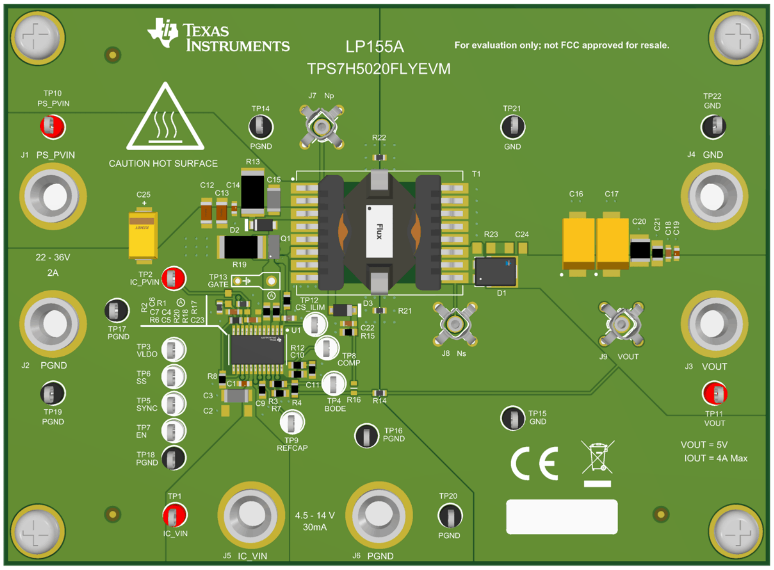


Figure 3-5. TPS7H5020FLYEVM-EVAL Top View

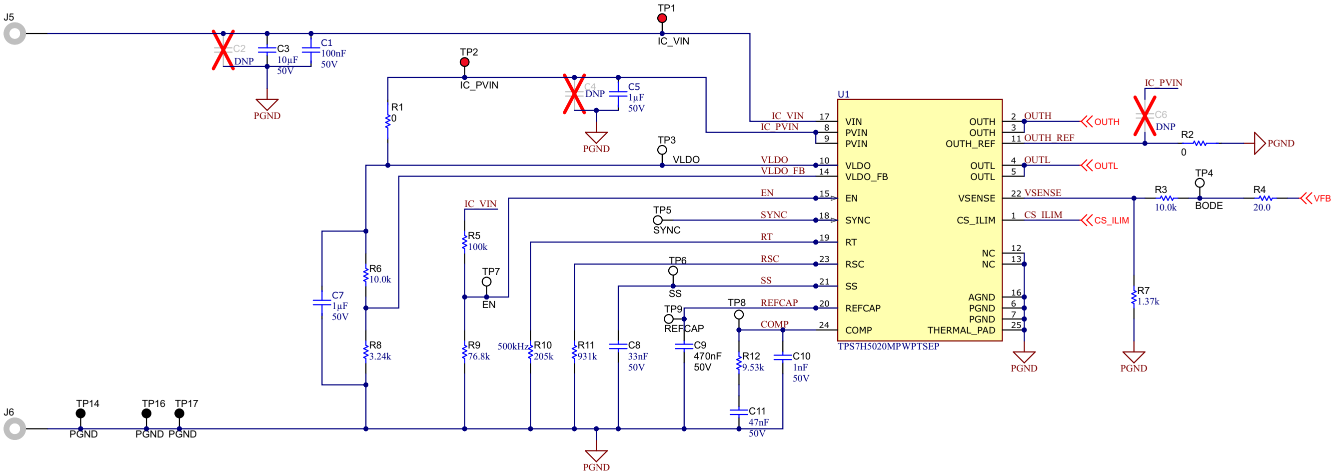


Figure 3-6. TPS7H5020FLYEVM-CVAL Controller Schematic

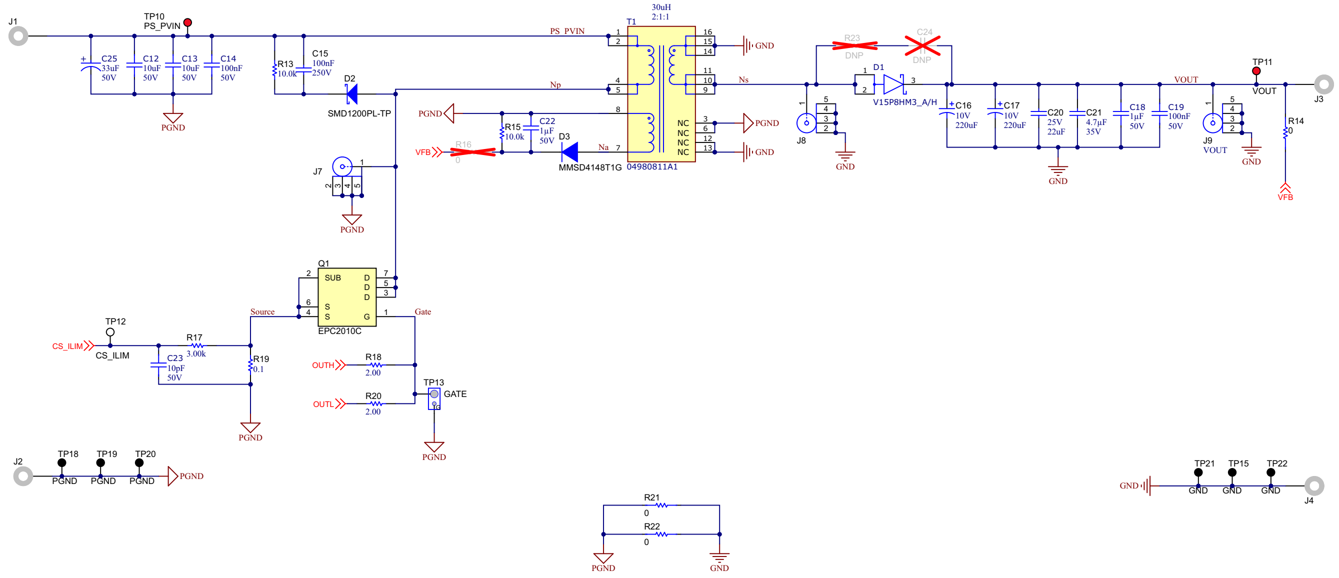


Figure 3-7. TPS7H5020FLYEVM-CVAL Power Stage Schematic

4 Irradiation Facility and Setup

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

- Texas A&M University (TAMU) Cyclotron Radiation Effects Facility using a K500 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 ≈4.00×10^4 to 1.00×10^5 ions/cm^2 ·s was used to provide heavy-ion fluences of 1.00×10^{7} . The TAMU facility uses a beam port that has a 1-mil Aramica window to allow in-air testing while maintaining the vacuum within the particle accelerator. The in-air gap between the device and the ion beam port window was maintained at 40mm for all runs.
- Michigan State University (MSU) Facility for Rare Isotope Beams (FRIB) using a K500 superconducting cyclotron (KSEE) 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 40mm × 40mm square cross-sectional area for the in-air and vacuum scintillators. 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 ≈10^5 was used to provide heavy-ion fluences of 1.00×10^{7} . The KSEE facility uses a beam port that has a 3-mil polyethylene naphthalate (PEN) window to allow in-air testing while maintaining the vacuum within the particle accelerator. The in-air gap between the device and the ion beam port window was maintained at 60mm for all runs.

For the experiments conducted on this report, there was 2 ions were used, ^{165}Ho and ^{169}Tm. Both were used to obtain LET$_{EFF}$ of 75MeV·cm^2/mg. The total kinetic energies for the ions were:

- ^{165}Ho = 2.474GeV (15MeV/nucleon)
  - Ion uniformity for these experiments was between 95% and 96%
- ^{169}Tm = 3.295GeV (19.5MeV/nucleon)
  - Ion uniformity for these experiments was 79.8%

Figure 4-1 shows the open-loop custom SEE evaluation module in front of the beam line at the TAMU facility.

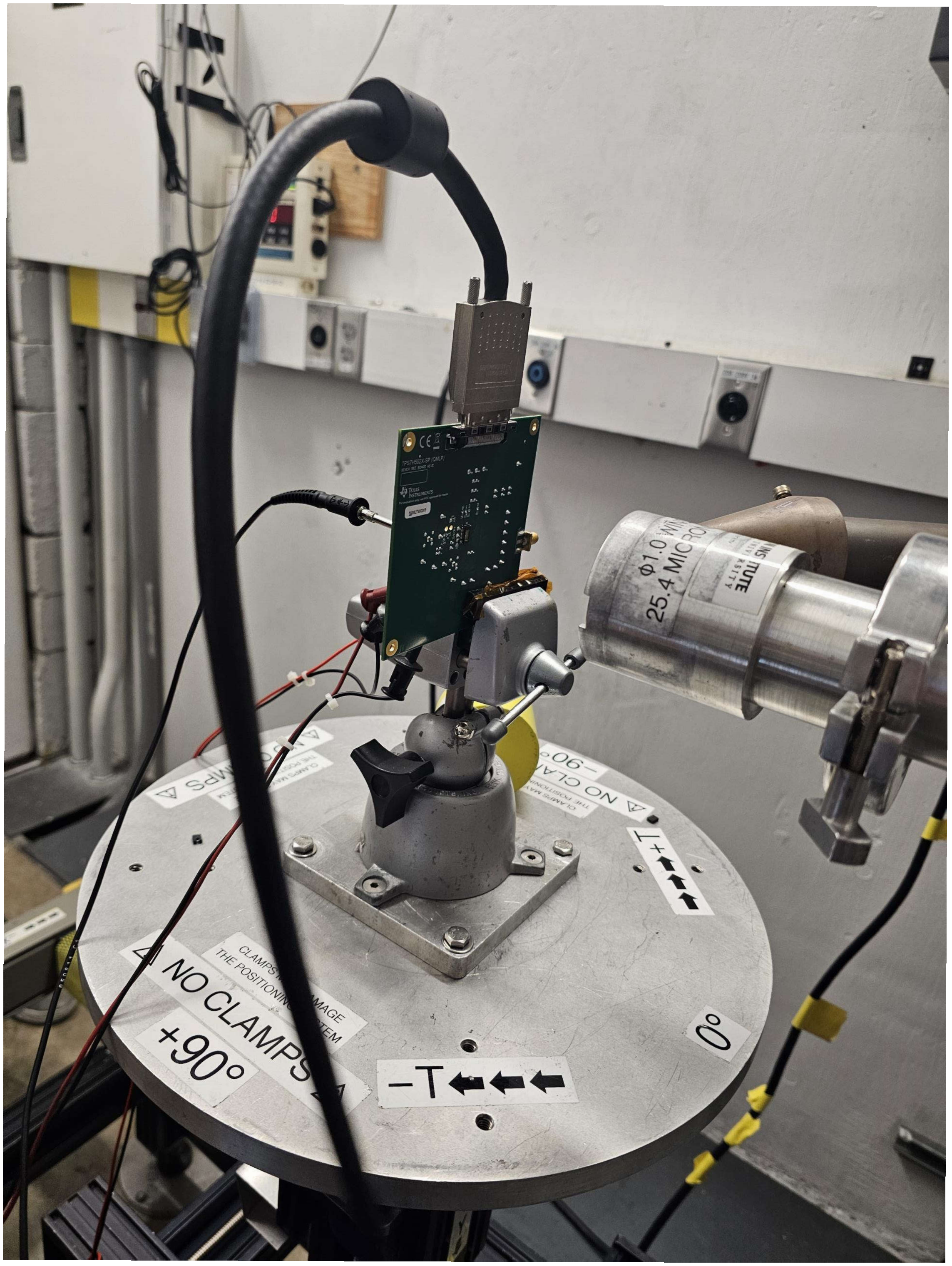
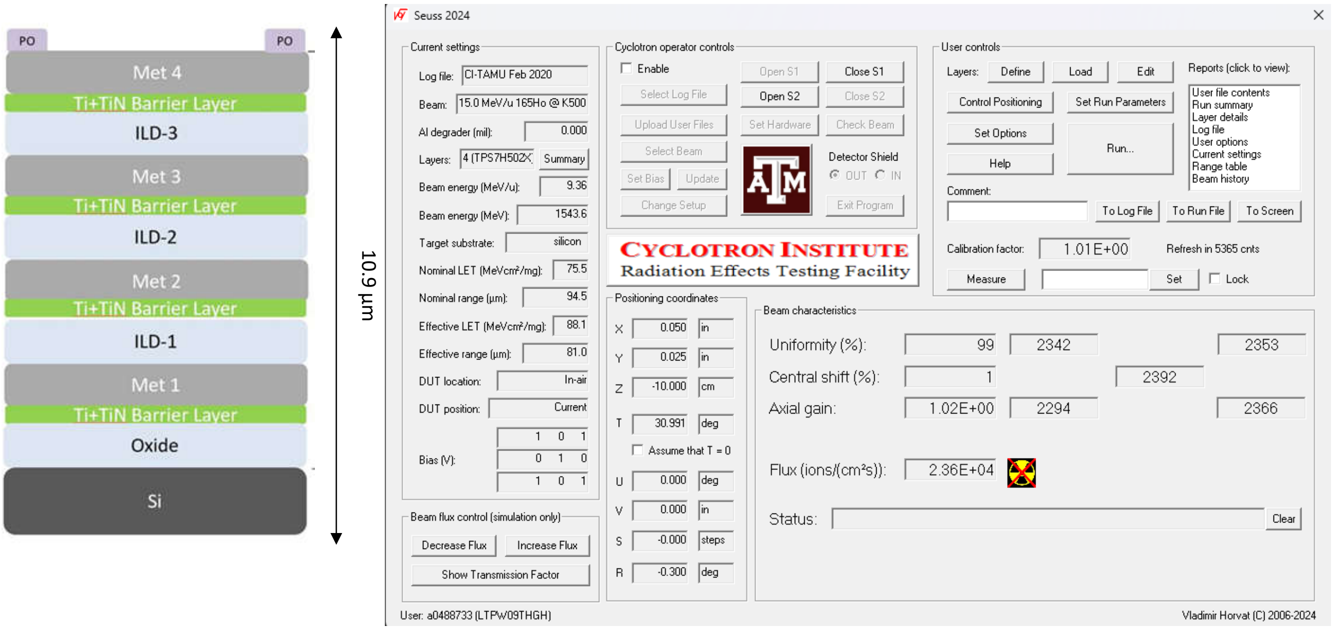


Figure 4-1. TPS7H502X-SP EVM in Front of the Heavy-Ion Beam Exit Port at the Texas A&M Cyclotron

5 LET_{EFF} and Range Calculation



Current settings

Log file: CI-TAMU Feb 2020
Beam: 15.0 MeV/u 165Ho @ K500
Al degrader (mil): 0.000
Layers: 4 (TPS7H502X
Beam energy (MeV/u): 9.36
Beam energy (MeV): 1543.6
Target substrate: silicon
Nominal LET (MeVcm²/mg): 75.5
Nominal range (µm): 94.5
Effective LET (MeVcm²/mg): 88.1
Effective range (µm): 81.0
DUT location: In-air
DUT position: Current
Bias (V): 1 0 1 / 0 1 0 / 1 0 1

Detector Shield ● OUT ○ IN

Positioning coordinates

X 0.050 in
Y 0.025 in
Z -10.000 cm
T 30.991 deg
☐ Assume that T = 0
U 0.000 deg
V 0.000 in
S -0.000 steps
R -0.300 deg

Comment:
Calibration factor: 1.01E+00
Refresh in 5365 cnts

Beam characteristics

Uniformity (%): 99 2342 2353
Central shift (%): 1 2392
Axial gain: 1.02E+00 2294 2366
Flux (ions/(cm²s)): 2.36E+04
Status:

User: a0488733 (LTPW09THGH)
Vladimir Horvat (C) 2006-2024

Figure 5-1. Generalized Cross-Section of the LBC7 Technology BEOL Stack on the TPS7H502X-SP [Left] and SEUSS 2024 Application Used to Determine Key Ion Parameters [Right]

The TPS7H502X-SP is fabricated in the TI Linear BiCMOS 250-nm process with a back-end-of-line (BEOL) stack consisting of 4 levels of standard thickness aluminum. The total stack height from the surface of the passivation to the silicon surface is 10.9 µm based on nominal layer thickness as shown in Figure 5-1.

Accounting for energy loss through the degrader, copper foil, beam port window, air gap, and the BEOL stack of the TPS7H502X-SP, the effective LET (LET_{EFF}) at the surface of the silicon substrate and the range was determined with:

- SEUSS 2022 software (provided by TAMU and based on the latest SRIM-2013 [7] models)
- MSU Stack-Up Calculator (provided by MSU FRIB and based on latest SRIM-2013 [7] models)

The results are shown in Ion LET_{EFF} and Range in Silicon.

Table 5-1. Ion LET_{EFF} and Range in Silicon

Facility	Beam Energy (MeV/ nucleon)	Ion Type	Degrader Steps (#)	Degrader Angle (°)	Copper Foil Width (µm)	Beam Port Window	Air Gap (mm)	Angle of Incidence	LET_{EFF} (MeV·cm^2/ mg)	Range in Silicon (µm)
TAMU	15	^{165}Ho	0	0	-	1-mil Aramica	40	0	75	95.7
KSEE	19.5	^{169}Tm	-	-	5	3-mil PEN	60	0	75	89.8

6 Test Setup and Procedures

There were two input supplies used to power the TPS7H502X-SP which provided V_{IN} and EN. The V_{IN} for the device was provided via Ch. 3 of an N6705C power module and ranged from 4.5V to 14V for SEL, SEB/SEGR, and SET testing. The EN of the device was driven by an E36311A power supply and was either forced to 0V or 4.5V to enable or disable the device. A NI PXIe-6341 DAQ was used to drive V_{SNS} and V_{COMP}. V_{LDO} had 3 programmable voltages, 4.5V, 5V, or 5.5V and were selected by closing relays to connect to a feedback network on the EVM to select the required V_{LDO} voltage. Input ranges for the different modes and switching frequencies are shown below. Note that the P_{VIN} column denotes whether or not P_{VIN} (the driver stage input) was tied to V_{IN} or V_{LDO}.

Table 6-1. TPS7H502X-SP Mode Bias Ranges

Mode	V_{IN} (V)	P_{VIN}	V_{LDO} (V)	V_{SNS} (V)	V_{COMP} (V)	EN (V)	RT (Ω)	FSW (Hz)
Silicon	4.5-14	VIN	4.5-5.5	0.6	0.8	0/4.5	205k	500k
	4.5-14	VIN	4.5-5.5	0.6	1.45	0/4.5	1.07M	100k
	4.5-14	VIN	4.5-5.5	0.6	0.6	0/4.5	90.9k	1M
GaN	4.5-14	VLDO	4.5-5.5	0.6	0.6	0/4.5	205k	500k
	4.5-14	VLDO	4.5-5.5	0.6	0.925	0/4.5	1.07M	100k
	4.5-14	VLDO	4.5-5.5	0.6	0.45	0/4.5	90.9k	1M

The primary signal monitored during testing was GATE (OUTH and OUTL tied together on the EVM) and this was done so using a PXIe-5110 triggering using a pulse-width trigger at 20%. The other three signals monitored were REFCAP, V_{LDO}, and SS which were monitored on their own independent NI PXIe-5172 or NI PXIe-5162 cards. The two signals on the PXIe-5172 triggered on a 3% window, the SS signal triggered off of 500-mV below its nominal value.

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.

Equipment Settings and Parameters Used During the Open-Loop SEE Testing of the TPS7H502X-SP shows 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 TPS7H502X-SP.

Note that only the relay for the correct feedback network was driven by the PXIe-6341 for V_{LDO}, not the actual V_{LDO} voltage.

Table 6-2. Equipment Settings and Parameters Used During the Open-Loop SEE Testing of the TPS7H502X-SP

PIN NAME	EQUIPMENT USED	CAPABILITY	COMPLIANCE	RANGE OF VALUES USED
V_{IN}	N6705C (CH # 3)	20.4V, 50A	5A	2.5 to 7V
EN	E36311A (CH # 1)	5V,5A	0.1A	0V, 5V
V_{SNS}	PXIe-6341	±10V, ±5mA	N/A	0.6V
V_{COMP}	PXIe-6341	±10V, ±5mA	N/A	0.45V to 1.45V
V_{LDO}	PXIe-6341	±10V, ±5mA	N/A	0V, 5V
GATE	PXIe-5110	100 MS/s	—	100 MS/s
REFCAP	PXIe-5172	100 MS/s	—	100 MS/s
V_{LDO}	PXIe-5172 (2)	100 MS/s	—	100 MS/s
SS	PXIe-5162	5 GS/s	—	100 MS/s

For testing of the TPS7H502X-SP in the flyback configuration V_{IN} was set to 12V and supplied through Ch. 1 of the N6705C. The input of the power stage was set to 28V and supplied through Ch. 3 of the N6705C. The programmable VLDO was set to 5V. For all flyback configuration testing PVIN was tied to VLDO putting the device in GaN mode. A Chroma E-Load in constant resistance mode was used to load the device with a resistance of 1.25Ω to provide a load of 4A. The primary signals monitored were GATE (the OUTH and OUTL tied together before the transformer) and V_{OUT} (the DC output after the transformer).

Table 6-3. Equipment Settings and Parameters Used During the Flyback Configuration SEE Testing of the TPS7H502X-SP

PIN NAME	EQUIPMENT USED	CAPABILITY	COMPLIANCE	RANGE OF VALUES USED
V_{IN} (V)	N6705C (CH # 1)	20.4V, 50A	10A	12V
Power Stage (V)	N6705C (CH # 3)	60V, 17.2A	10A	28V
GATE	PXIe-5110	100 MS/s	—	100MS/s
V_{OUT}	PXIe-5172	100 MS/s	—	100 MS/s
V_{OUT}	Chroma E36300	80A	Low	1.25Ω

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 test facilities. During the heavy-ion testing, the LabVIEW control program powered up the TPS7H502X-SP 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 pulse-width or window 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.

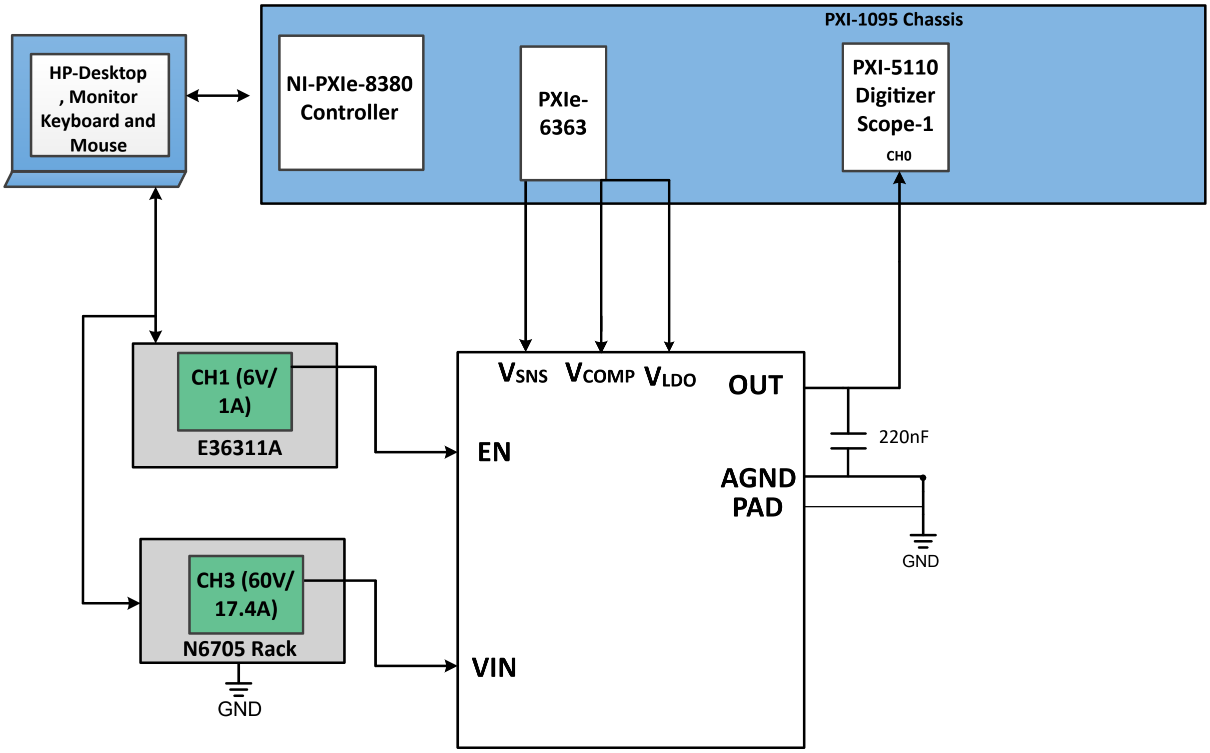


Figure 6-1. Block Diagram of the SEE Test Setup for the TPS7H502X-SP

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 PID controlled heat gun (MISTRAL 6 System (120V, 2400W)). The temperature of the die was constantly monitored during testing at TAMU through an IR camera integrated into the control loop to create closed-loop temperature control. The die temperature was verified using a standalone FLIR thermal camera prior to exposure to heavy ions at KSEE.

The species used for the SEL testing was ^{165}Ho at 15MeV/nucleon and ^{169}Tm at 19.5 MeV/nucleon. For both ions an angle of incidence of 0° was used to achieve a LET_{EFF} of ≈75MeV·cm^2/mg (for more details refer to Ion LET_{EFF} and Range in Silicon). The kinetic energy in the vacuum for ^{165}Ho is 2.474GeV and ^{169}Tm is 3.295GeV. Flux of approximately 4×10^4 to 1×10^5 ions×cm^2/s and a fluence of ≈10^7 ions/cm^2 per run was used. Run duration to achieve this fluence was ≈2 minutes. The 6 production and 7 pre-production devices were powered up and exposed to the heavy-ions using the maximum recommended input voltage of 14V and max programmable V_{LDO} voltage of 5.5V. Depending on the operational mode PVIN was either tied to VIN or VLDO, for more information refer to the test setup and procedures. No SEL events were observed during all four runs, indicating that the TPS7H502X-SP is SEL-free up to 75MeV·cm^2/mg.Table 7-1 shows the SEL test conditions and results. Figure 7-1 and Figure 7-2 show a plot of the current versus time for runs #8 and 9 respectively.

Table 7-1. Summary of TPS7H502X-SP SEL Test Condition and Results

Run #	Unit #	Facility	Device Type	Production Type	Mode	Ion	LET_{EFF} (MeV·cm^2/mg)	Flux (ions×cm^2/s)	Fluence (ions/cm^2)	V_{IN} (V)	P_{VIN} (V)	V_{LDO}	SEL (# Events)
1	1	TAMU	TPS7H5020-SP	Pre	Silicon	^{165}Ho	75	4.42×10^4	1×10^7	14	14	5.5	0
2	2	TAMU	TPS7H5020-SP	Pre	Silicon	^{165}Ho	75	1.10×10^5	1×10^7	14	14	5.5	0
3	3	TAMU	TPS7H5020-SP	Pre	GaN	^{165}Ho	75	1.10×10^5	1×10^7	14	5.5	5.5	0
4	4	TAMU	TPS7H5021-SP	Pre	Silicon	^{165}Ho	75	1.04×10^5	1×10^7	14	14	5.5	0
5	5	TAMU	TPS7H5021-SP	Pre	GaN	^{165}Ho	75	1.11×10^5	1×10^7	14	5.5	5.5	0
6	6	TAMU	TPS7H5021-SP	Pre	Silicon	^{165}Ho	75	9.14×10^4	1×10^7	14	14	5.5	0
7	7	TAMU	TPS7H5021-SP	Pre	GaN	^{165}Ho	75	9.50×10^4	1×10^7	14	5.5	5.5	0
8	8	TAMU	TPS7H5020-SP	Final	Silicon	^{165}Ho	75	1.12×10^5	1×10^7	14	14	5.5	0
9	9	TAMU	TPS7H5021-SP	Final	GaN	^{165}Ho	75	1.11×10^5	1×10^7	14	5.5	5.5	0
10	10	TAMU	TPS7H5020-SP	Final	Silicon	^{165}Ho	75	1.01×10^5	1×10^7	14	14	5.5	0
11	11	TAMU	TPS7H5021-SP	Final	GaN	^{165}Ho	75	1.13×10^5	1×10^7	14	5.5	5.5	0
12	12	KSEE	TPS7H5020-SP	Final	Silicon	^{169}Tm	75	1.03×10^5	1×10^7	14	14	5.5	0
13	13	KSEE	TPS7H5021-SP	Final	Silicon	^{169}Tm	75	1.02×10^5	1×10^7	14	14	5.5	0

Using the MFTF method described in *Single-Event Effects (SEE) Confidence Interval Calculations* application report and combining (or summing) the fluences of the four runs at 125°C (13×10^7), the upper-bound cross-section (using a 95% confidence level) is calculated as:

$\sigma_{SEL} \leq 2.84 \times 10^{-8}$ cm^2/device for LET_{EFF} = 75MeV·cm^2/mg and T = 125°C.

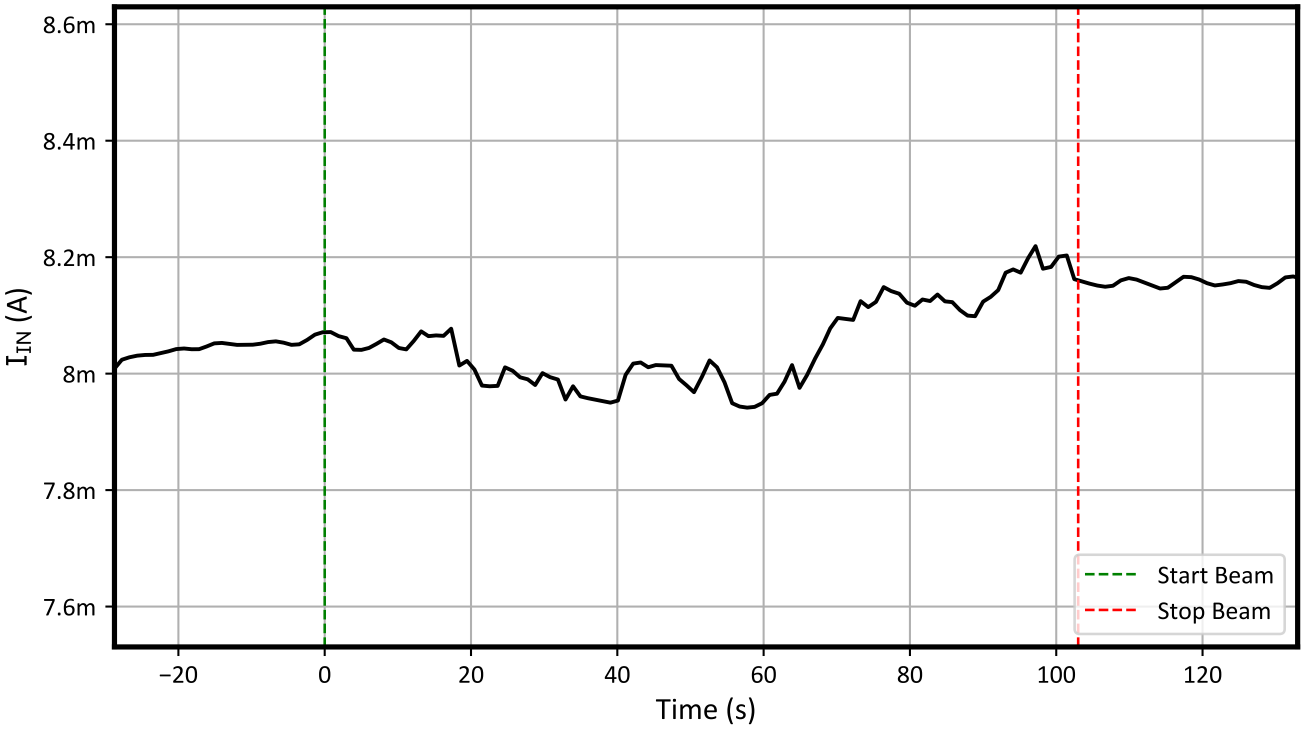


Figure 7-1. Current versus Time for Run # 8 of the TPS7H5020-SP at T = 125°C in Silicon Mode

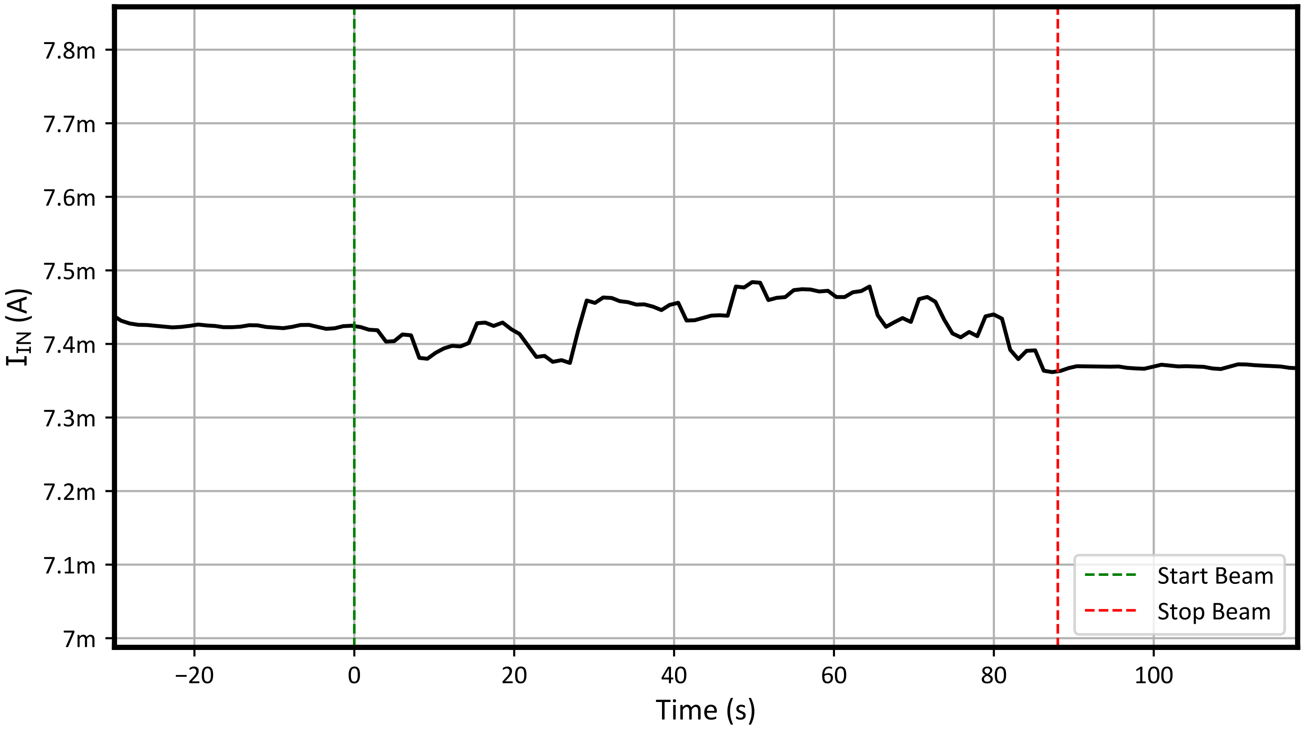


Figure 7-2. Current versus Time for Run #9 of the TPS7H5021-SP at T = 125°C in GaN Mode

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 (using CH # 1 of a E36311A Keysight PS). During the SEB/SEGR testing with the device enabled/disabled, not a single input current event was observed.

The species used for the SEB testing was ^{165}Ho at 15MeV/nucleon and ^{169}Tm at 19.5MeV/nucleon. For both ions an angle of 0° was used to achieve a LET_{EFF} of ≈75MeV·cm^2/mg (for more details refer to Ion LET_{EFF} and Range in Silicon). The kinetic energy in the vacuum for ^{165}Ho is 2.474GeV and ^{169}Tm is 3.295GeV. Flux of approximately 4×10^4 to 1×10^5 ions×cm^2/s and a fluence of ≈10^7 ions/cm^2 was used for the run. Run duration to achieve this fluence was ≈2 minutes. The 6 production devices and 7 pre-production devices (same as used in SEL testing) were powered up and exposed to the heavy-ions using the maximum recommended bias conditions. No SEB/SEGR current events were observed during the 26 runs, indicating that the TPS7H502X-SP is SEB/SEGR-free up to LET_{EFF} = 75MeV·cm^2/mg and across the full electrical specifications.Summary of TPS7H502X-SP SEB/SEGR Test Condition and Resultsshows the SEB/SEGR test conditions and results.

Table 7-2. Summary of TPS7H502X-SP SEB/SEGR Test Condition and Results

RUN #	UNIT #	Facility	Device Type	Production Type	Mode	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions×cm^2/s)	FLUENCE (ions/cm^2)	ENABLED STATUS	V_{IN} (V)	P_{VIN} (V)	V_{LDO} (V)	SEB EVENT ?
14	1	TAMU	TPS7H5020-SP	Pre	Silicon	^{165}Ho	75	3.76×10^4	9.99×10^6	EN	14	14	5.5	No
15	1	TAMU	TPS7H5020-SP	Pre	Silicon	^{165}Ho	75	3.83×10^4	9.99×10^6	DIS	14	14	5.5	No
16	2	TAMU	TPS7H5020-SP	Pre	Silicon	^{165}Ho	75	1.10×10^5	1.00×10^7	EN	14	14	5.5	No
17	2	TAMU	TPS7H5020-SP	Pre	Silicon	^{165}Ho	75	1.00×10^5	1.00×10^7	DIS	14	14	5.5	No
18	3	TAMU	TPS7H5020-SP	Pre	GaN	^{165}Ho	75	1.05×10^5	1.00×10^7	EN	14	5.5	5.5	No
19	3	TAMU	TPS7H5020-SP	Pre	GaN	^{165}Ho	75	1.60×10^5	1.00×10^7	DIS	14	5.5	5.5	No
20	4	TAMU	TPS7H5021-SP	Pre	Silicon	^{165}Ho	75	1.00×10^5	1.00×10^7	EN	14	14	5.5	No
21	4	TAMU	TPS7H5021-SP	Pre	Silicon	^{165}Ho	75	1.14×10^5	1.00×10^7	DIS	14	14	5.5	No
22	5	TAMU	TPS7H5021-SP	Pre	GaN	^{165}Ho	75	1.04×10^5	1.00×10^7	EN	14	5.5	5.5	No
23	5	TAMU	TPS7H5021-SP	Pre	GaN	^{165}Ho	75	1.00×10^5	1.00×10^7	DIS	14	5.5	5.5	No
24	6	TAMU	TPS7H5021-SP	Pre	Silicon	^{165}Ho	75	1.09×10^5	1.00×10^7	EN	14	14	5.5	No
25	6	TAMU	TPS7H5021-SP	Pre	Silicon	^{165}Ho	75	9.34×10^4	1.00×10^7	DIS	14	14	5.5	No

Table 7-2. Summary of TPS7H502X-SP SEB/SEGR Test Condition and Results (continued)

RUN #	UNIT #	Facility	Device Type	Production Type	Mode	ION	LET$_{EFF}$ (MeV·cm^2/mg)	FLUX (ions×cm^2/s)	FLUENCE (ions/cm^2)	ENABLED STATUS	V$_{IN}$ (V)	P$_{VIN}$ (V)	V$_{LDO}$ (V)	SEB EVENT ?
26	7	TAMU	TPS7H5021-SP	Pre	GaN	^{165}Ho	75	1.13 x 10^5	1.00 x 10^7	EN	14	5.5	5.5	No
27	7	TAMU	TPS7H5021-SP	Pre	GaN	^{165}Ho	75	1.10 x 10^5	1.00 x 10^7	DIS	14	5.5	5.5	No
28	8	TAMU	TPS7H5020-SP	Final	Silicon	^{165}Ho	75	1.16 x 10^5	1.00 x 10^7	EN	14	14	5.5	No
29	8	TAMU	TPS7H5020-SP	Final	Silicon	^{165}Ho	75	1.19 x 10^5	1.00 x 10^7	DIS	14	14	5.5	No
30	9	TAMU	TPS7H5020-SP	Final	GaN	^{165}Ho	75	1.12 x 10^5	1.00 x 10^7	EN	14	5.5	5.5	No
31	9	TAMU	TPS7H5020-SP	Final	GaN	^{165}Ho	75	1.10 x 10^5	1.00 x 10^7	DIS	14	5.5	5.5	No
32	10	TAMU	TPS7H5021-SP	Final	Silicon	^{165}Ho	75	1.01 x 10^5	1.00 x 10^7	EN	14	14	5.5	No
33	10	TAMU	TPS7H5021-SP	Final	Silicon	^{165}Ho	75	9.50 x 10^4	1.00 x 10^7	DIS	14	14	5.5	No
34	11	TAMU	TPS7H5021-SP	Final	GaN	^{165}Ho	75	1.15 x 10^5	1.00 x 10^7	EN	14	5.5	5.5	No
35	11	TAMU	TPS7H5021-SP	Final	GaN	^{165}Ho	75	1.14 x 10^5	1.00 x 10^7	DIS	14	5.5	5.5	No
36	12	KSEE	TPS7H5020-SP	Final	Silicon	^{169}Tm	75	1.06 x 10^5	1.00 x 10^7	EN	14	14	5.5	No
37	12	KSEE	TPS7H5020-SP	Final	Silicon	^{169}Tm	75	9.65 x 10^4	1.00 x 10^7	DIS	14	14	5.5	No
38	13	KSEE	TPS7H5021-SP	Final	Silicon	^{169}Tm	75	1.06 x 10^5	1.00 x 10^7	EN	14	14	5.5	No
39	13	KSEE	TPS7H5021-SP	Final	Silicon	^{169}Tm	75	1.04 x 10^5	1.00 x 10^7	DIS	14	14	5.5	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:

$\sigma_{SEB} \leq 1.42 \times 10^{-8}$ cm^2/device for LET$_{EFF}$ = 75MeV·cm^2/mg and T = 25°C.

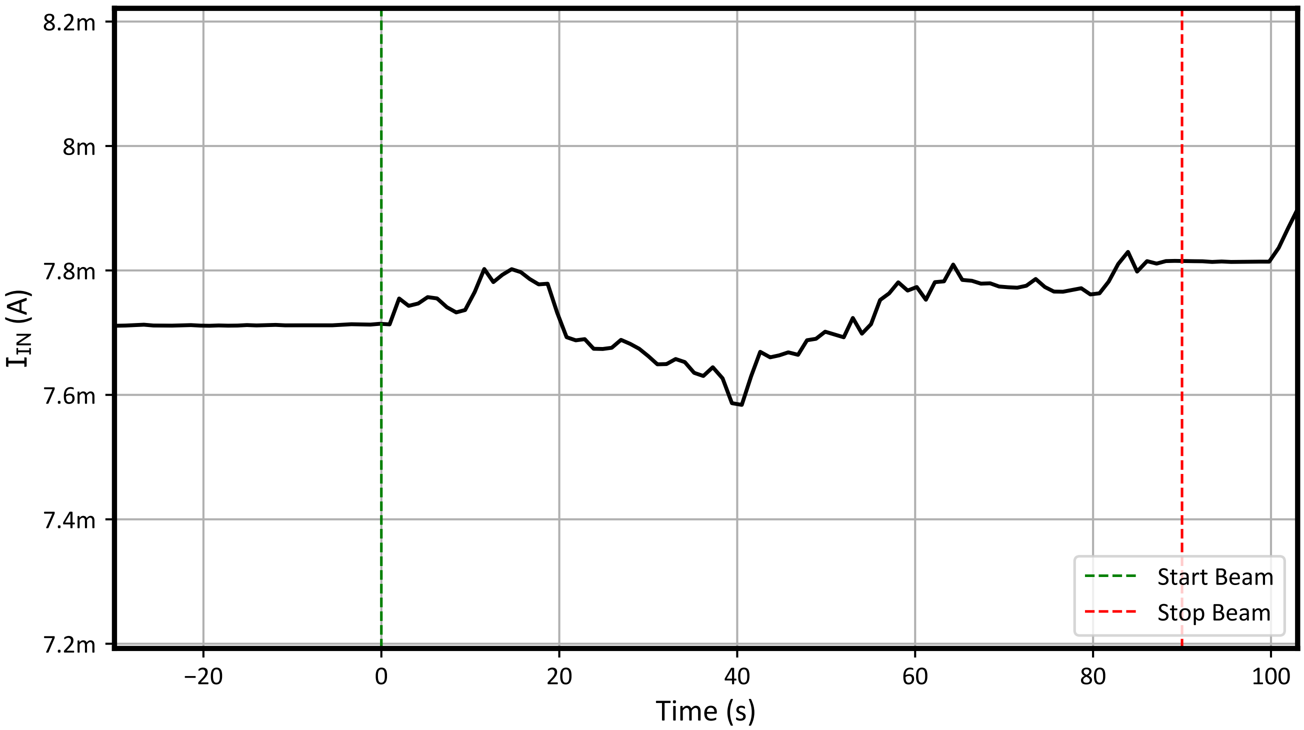


Figure 7-3. SEB On Run #28 TPS7H5020-SP Silicon Mode

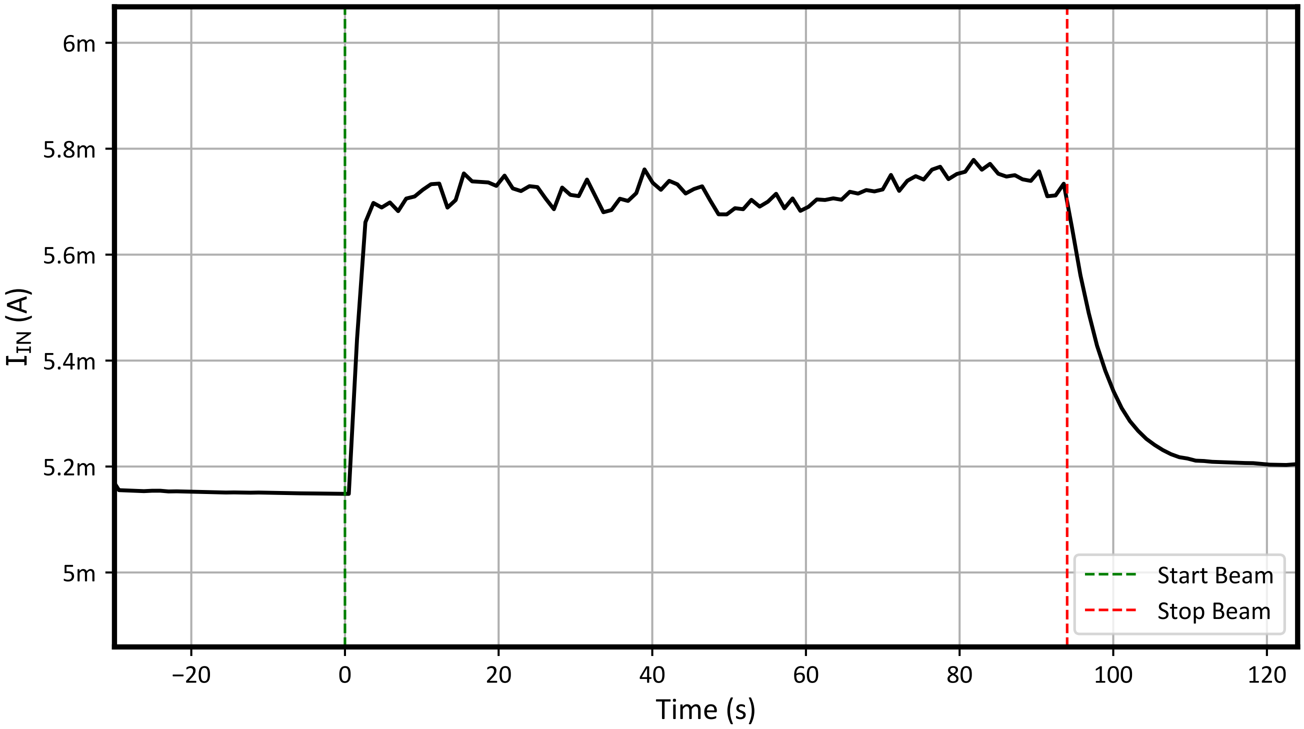


Figure 7-4. SEB Off Run #29 TPS7H5020-SP Silicon Mode

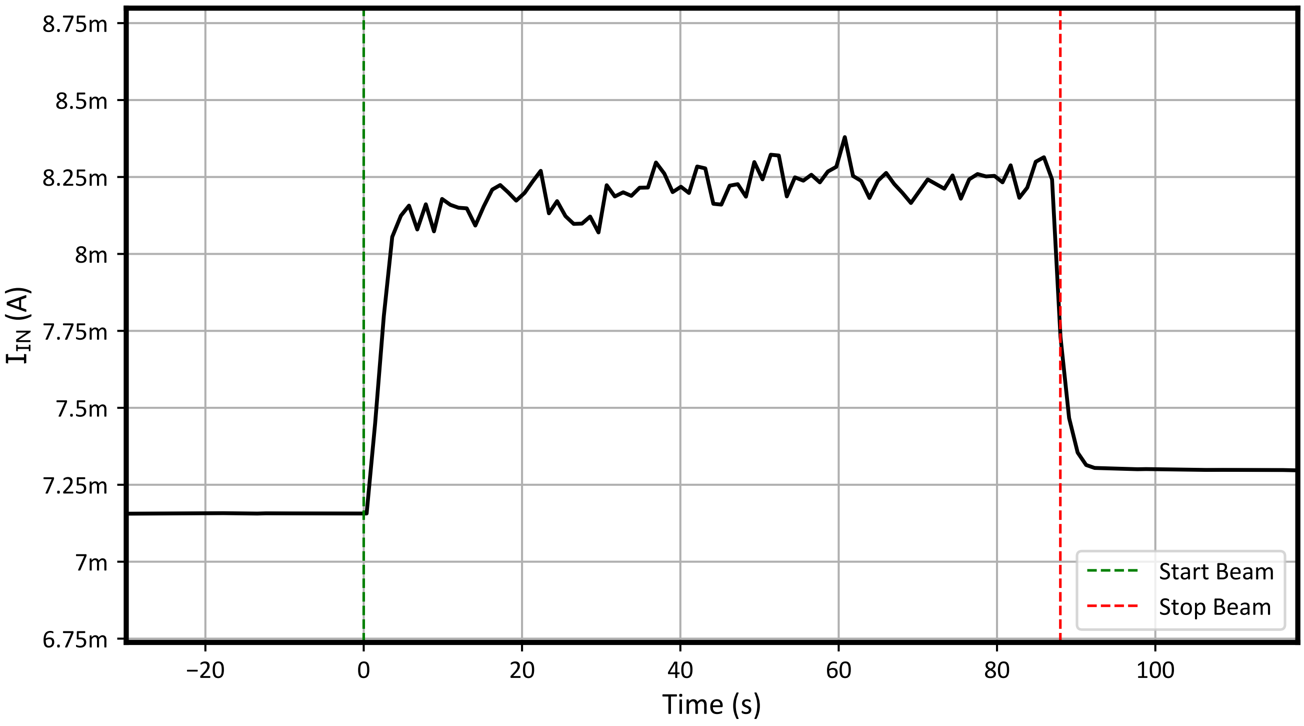


Figure 7-5. SEB On Run #32 TPS7H5021-SP GaN Mode

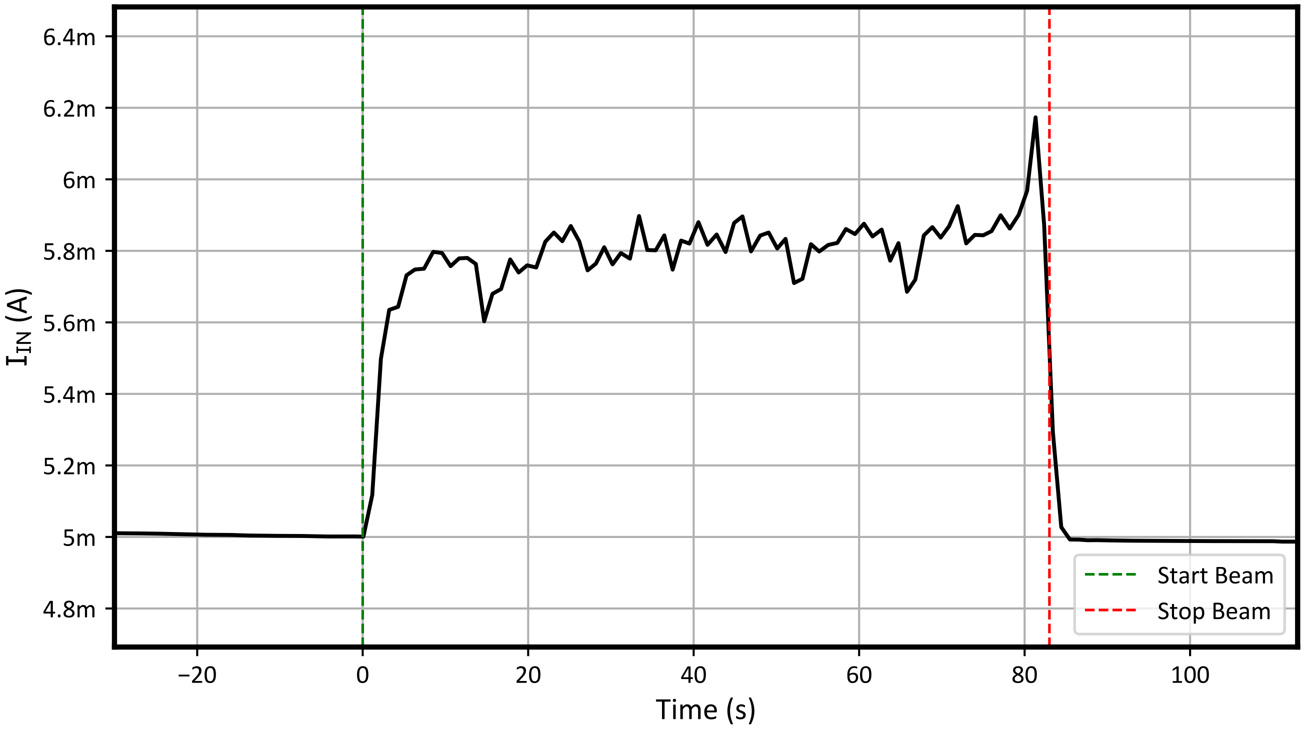


Figure 7-6. SEB Off Run #33 TPS7H5021-SP GaN Mode

8 Single-Event Transients (SET)

SET are defined as heavy-ion-induced transients upsets on the GATE (OUTH and OUTL tied together), REFCAP, V_{LDO}, and SS of the TPS7H502X-SP. When conducting testing on the device in flyback configuration the VOUT of the device (the DC signal after the transformer on the EVM) was also monitored.

Testing was performed at room temperature (no external temperature control applied). The heavy-ions species used for the SET testing was ^{165}Ho at 15 MeV/nucleon and ^{169}Tm at 19.5 MeV/nucleon (for more details refer to Ion LET_{EFF} and Range in Silicon). Flux of ≈10^5 ions×cm^2/s and a fluence of ≈10^7 ions/cm^2, per run were used for the SET characterization discussed in this chapter.

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

Note[1]: Only one Signal was used as a trigger source at a time, this table presents all possible sources for a given scope, the same is valid for the trigger type. All percentage specified on the trigger value are deviation from the nominal value.

Note[2]: The trigger signal V_{OUT} is only valid for and was only monitored during the flyback configuration testing on the flyback EVM.

Table 8-1. Scope Settings

Scope Model	Trigger Signal[1]	Trigger Type	Trigger Value	Record Length	Sample Rate
PXIe-5110	GATE	Pulse-Width	± 20%	50k	100MS/s
PXIe-5172 (1)	REFCAP	Window	± 3 %	50k	100MS/s
PXIe-5172 (2)	V_{LDO}	Window	± 3 %	50k	100MS/s
PXIe-5162	SS	Edge/Negative	0.5V	50k	100MS/s
PXIe-5172 (3)	V_{OUT} [2]	Window	± 3 %	50k	100MS/s

Open-Loop Configuration

The primary focus of SETs were heavy-ion-induced transient upsets on output signal GATE (OUTH and OUTL tied together). SET testing was done at room temperature at ^{165}Ho which produced a LET_{EFF} of 75 MeV·cm^2/mg. GATE was monitored using a NI PXIe-5110. During testing the scope was set to trigger if the signal exceeded |20%| from nominal using a pulse width trigger. During all SET testing, there was one type of transient recorded that was self-recoverable. The REFCAP, V_{LDO}, and SS signals monitored on the PXIe-5172 and PXIe-5162 scopes did not have any recorded transients. Because the V_{LDO} signal had a window trigger on it, being transient free shows that there is no overshoot on the device at 75 MeV·cm^2/mg.

The SET results for 2 production and 7 pre-production devices are shown below in the following tables. The transient signature on GATE is shown and the number of transients across the runs, voltages, and frequencies is shown. Since only this transient signature occurred there is high confidence that the TPS7H502X-SP is SEFI free and the recorded transient signature does not show any overshoot indicating that the TPS7H502X-SP is safe for GaN operations. Note that for all testing V_{LDO} was programmed to be 5V except for the cases where V_{IN}=P_{VIN}=4.5V in which case it was programmed to be 4.5V as well.

The upper-bound cross-sections for all bias conditions are shown inFigure 8-1.

Table 8-2. Summary of TPS7H502X-SP Open-Loop SET Test Condition and Results

RUN #	UNIT #	Facility	Device Type	Production Type	Mode	V_{IN} (V)	F_{SW} (Hz)	ION	LET_{EFF} (MeV·cm²/mg)	FLUX (ions×cm²/s)	FLUENCE (ions/cm²)	# GATE ≥ |20%|	# REFCAP ≥ |3%|	# VLDO ≥ |3%|	# SS Triggers
40	2	TAMU	TPS7H5020-SP	Pre	Silicon	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	51	0	0	0
41	2	TAMU	TPS7H5020-SP	Pre	Silicon	12	100k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	22	0	0	0
42	2	TAMU	TPS7H5020-SP	Pre	Silicon	12	1M	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	0	0	0	0
43	2	TAMU	TPS7H5020-SP	Pre	GaN	4.5	1M	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	0	0	0	0
44	2	TAMU	TPS7H5020-SP	Pre	GaN	4.5	1M	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	0	0	0	0
45	2	TAMU	TPS7H5020-SP	Pre	GaN	4.5	1M	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	0	0	0	0
46	2	TAMU	TPS7H5020-SP	Pre	GaN	4.5	100k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	66	0	0	0
47	2	TAMU	TPS7H5020-SP	Pre	GaN	4.5	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	43	0	0	0
48	2	TAMU	TPS7H5020-SP	Pre	Silicon	12	100k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	32	0	0	0
49	2	TAMU	TPS7H5020-SP	Pre	Silicon	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	42	0	0	0
50	3	TAMU	TPS7H5020-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	—	0	0	0
51	3	TAMU	TPS7H5020-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	45	0	0	0
52	3	TAMU	TPS7H5020-SP	Pre	GaN	12	100k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	48	0	0	0
53	3	TAMU	TPS7H5020-SP	Pre	GaN	12	1M	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	4	0	0	0
54	3	TAMU	TPS7H5020-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	59	0	0	0
55	3	TAMU	TPS7H5020-SP	Pre	Silicon	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	16	0	0	0
56	3	TAMU	TPS7H5020-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00×10^{5}	1.00×10^{7}	41	0	0	0

Table 8-2. Summary of TPS7H502X-SP Open-Loop SET Test Condition and Results (continued)

RUN #	UNIT #	Facility	Device Type	Production Type	Mode	V_{IN} (V)	F_{SW} (Hz)	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions×cm^2/s)	FLUENCE (ions/cm^2)	# GATE ≥ |20%|	# REFCAP ≥ |3%|	# VLDO ≥ |3%|	# SS Triggers
57	3	TAMU	TPS7H5020-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	37	0	0	0
58	4	TAMU	TPS7H5021-SP	Pre	Silicon	12	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	73	0	0	0
59	4	TAMU	TPS7H5021-SP	Pre	Silicon	12	100k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	40	0	0	0
60	4	TAMU	TPS7H5021-SP	Pre	Silicon	12	1M	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	0	0	0	0
61	4	TAMU	TPS7H5021-SP	Pre	GaN	4.5	1M	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	3	0	0	0
62	4	TAMU	TPS7H5021-SP	Pre	GaN	4.5	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	62	0	0	0
63	4	TAMU	TPS7H5021-SP	Pre	GaN	4.5	100k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	78	0	0	0
64	5	TAMU	TPS7H5021-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	21	0	0	0
65	5	TAMU	TPS7H5021-SP	Pre	GaN	12	100k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	41	0	0	0
66	5	TAMU	TPS7H5021-SP	Pre	GaN	12	1M	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	6	0	0	0
67	5	TAMU	TPS7H5021-SP	Pre	GaN	4.5	1M	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	0	0	0	0
68	5	TAMU	TPS7H5021-SP	Pre	GaN	4.5	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	39	0	0	0
69	5	TAMU	TPS7H5021-SP	Pre	GaN	4.5	100k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	47	0	0	0
70	6	TAMU	TPS7H5021-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	31	0	0	0
71	6	TAMU	TPS7H5021-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	42	0	0	0
72	6	TAMU	TPS7H5021-SP	Pre	GaN	12	500k	^{165}Ho	75	1.00 × 10^5	1.00 × 10^7	25	0	0	0
73	14	TAMU	TPS7H5020-SP	Final	GaN	12	500k	^{165}Ho	75	1.11 × 10^5	1.00 × 10^7	123	—	—	—
74	14	TAMU	TPS7H5020-SP	Final	Silicon	12	500k	^{165}Ho	75	1.13 × 10^5	1.00 × 10^7	41	—	—	—

Table 8-2. Summary of TPS7H502X-SP Open-Loop SET Test Condition and Results (continued)

RUN #	UNIT #	Facility	Device Type	Production Type	Mode	V_{IN} (V)	F_{SW} (Hz)	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions×cm^2/s)	FLUENCE (ions/cm^2)	# GATE ≥ |20%|	# REFCAP ≥ |3%|	# VLDO ≥ |3%|	# SS Triggers
75	15	TAMU	TPS7H5021-SP	Final	GaN	12	500k	^{165}Ho	75	1.18×10^5	1.00×10^7	173	—	—	—
76	15	TAMU	TPS7H5021-SP	Final	Silicon	12	500k	^{165}Ho	75	1.16×10^5	1.00×10^7	55	—	—	—
77	12	KSEE	TPS7H5020-SP	Final	Silicon	12	500k	^{169}Tm	75	9.87×10^4	1.00×10^7	64	—	—	—
78	13	KSEE	TPS7H5021-SP	Final	Silicon	12	500k	^{169}Tm	75	1.06×10^5	1.00×10^7	79	—	—	—
83	16	KSEE	TPS7H5020-SP	Pre	Silicon	12	500k	^{109}Ag	49.1	9.70×10^4	1.00×10^7	5	—	—	—
84	17	KSEE	TPS7H5020-SP	Pre	GaN	12	500k	^{109}Ag	49.1	1.20×10^5	1.00×10^7	44	—	—	—

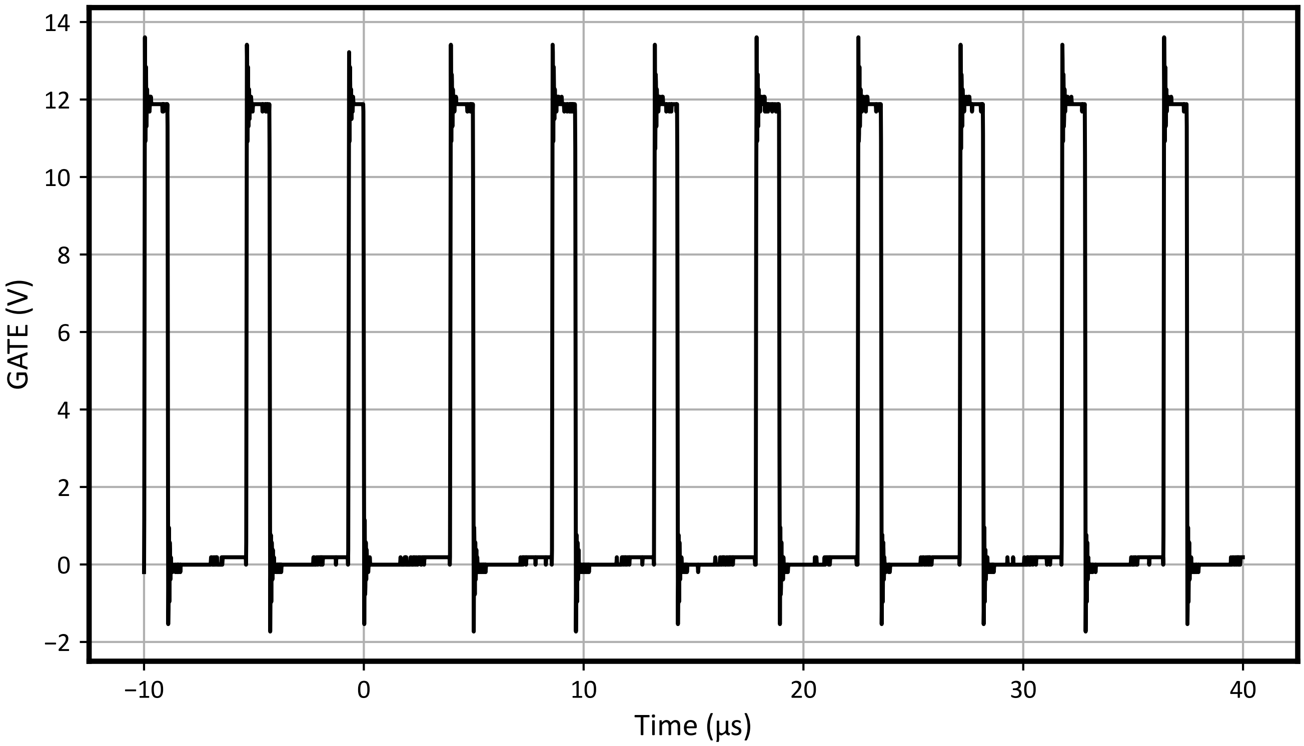


Figure 8-1. TPS7H5020-SP Silicon Mode GATE Pulse-Width Transient

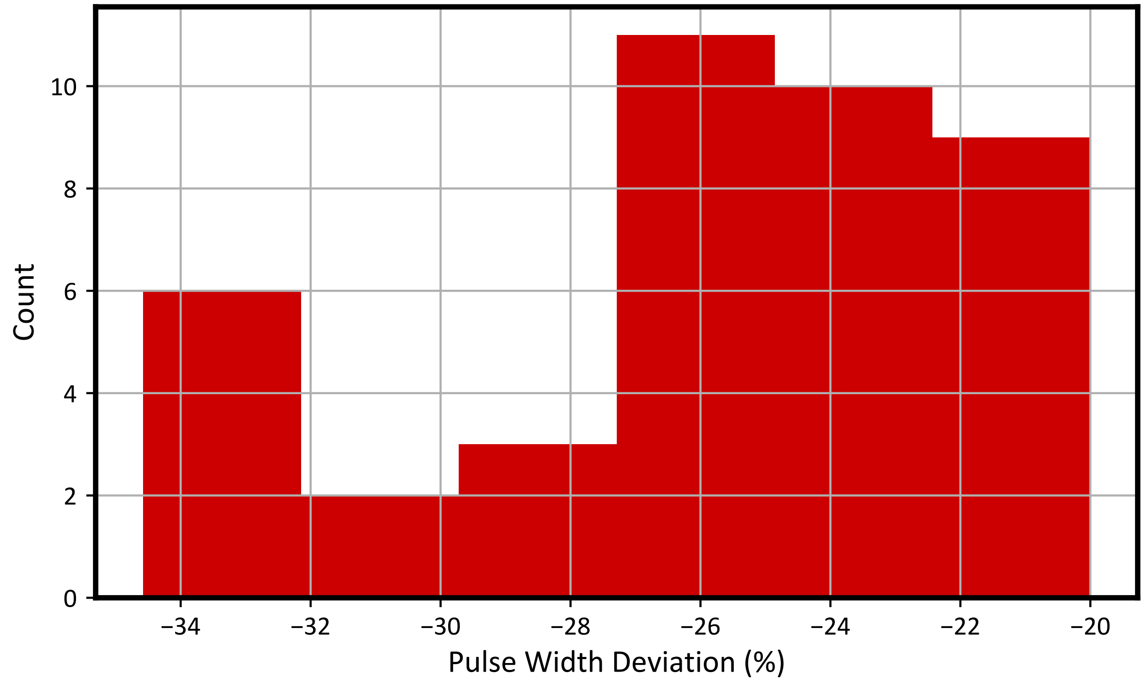


Figure 8-2. TPS7H5020-SP Silicon Mode GATE Pulse-Width Deviation Histogram

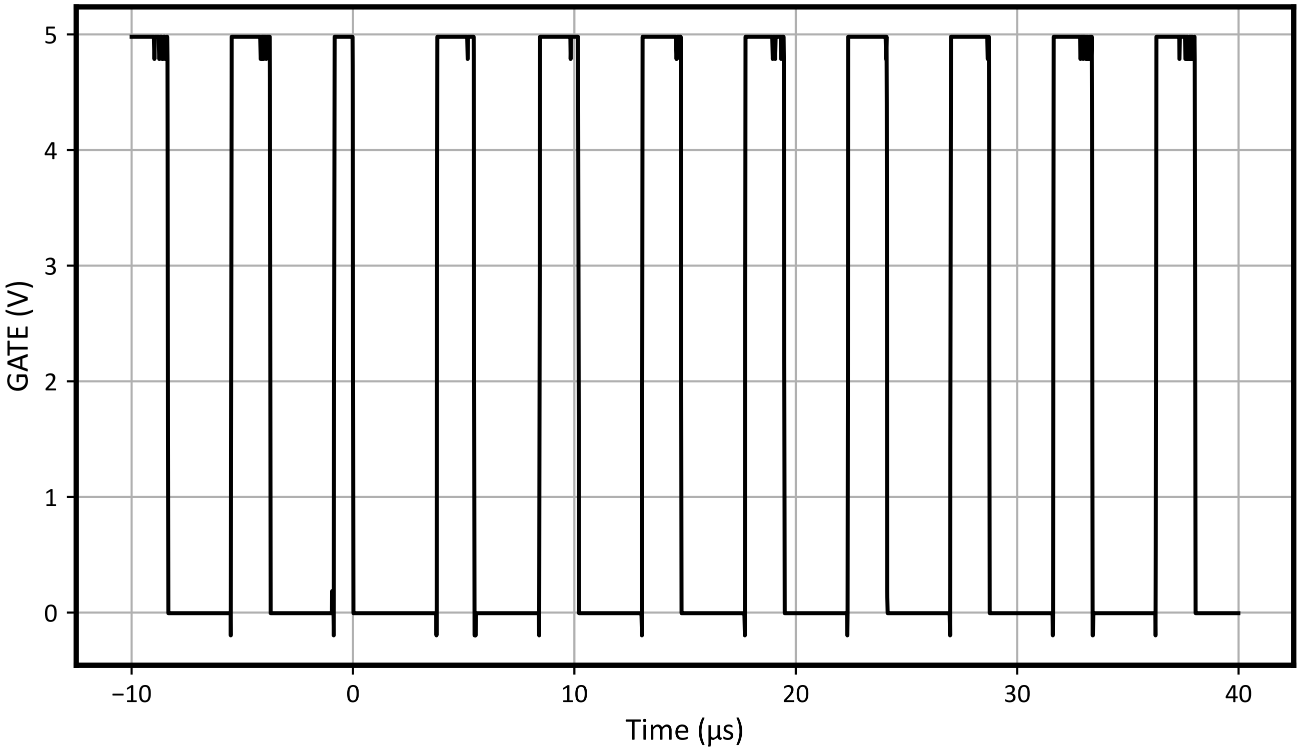


Figure 8-3. TPS7H5020-SP GaN Mode GATE Pulse-Width Transient

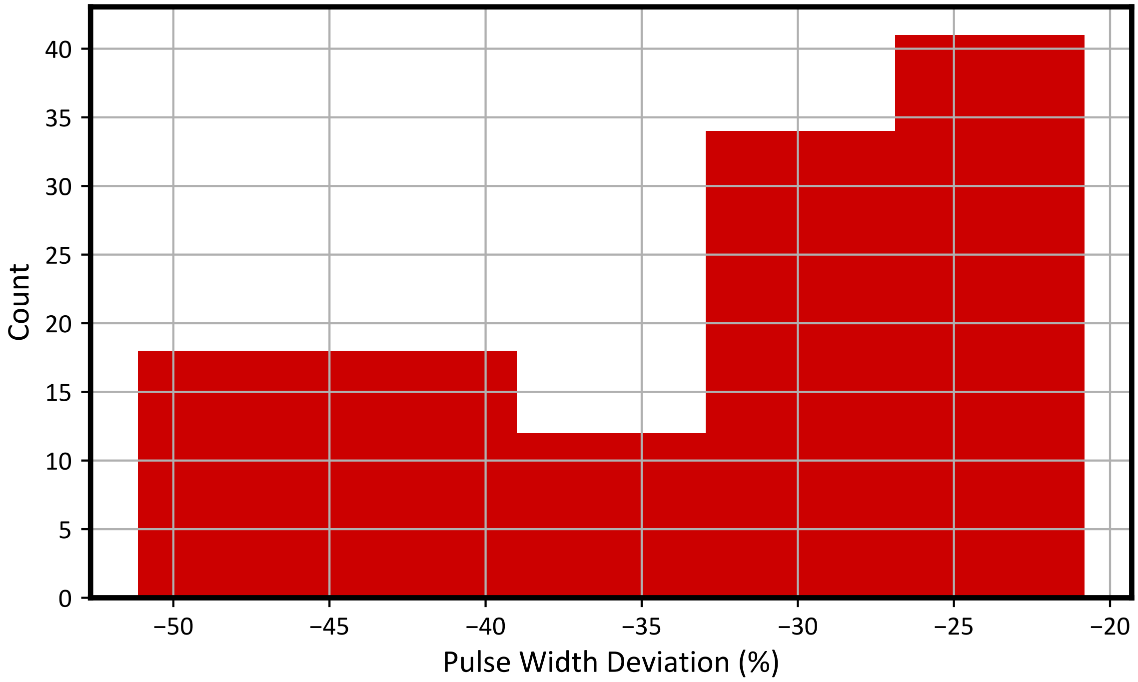


Figure 8-4. TPS7H5020-SP GaN Mode GATE Pulse-Width Deviation Histogram

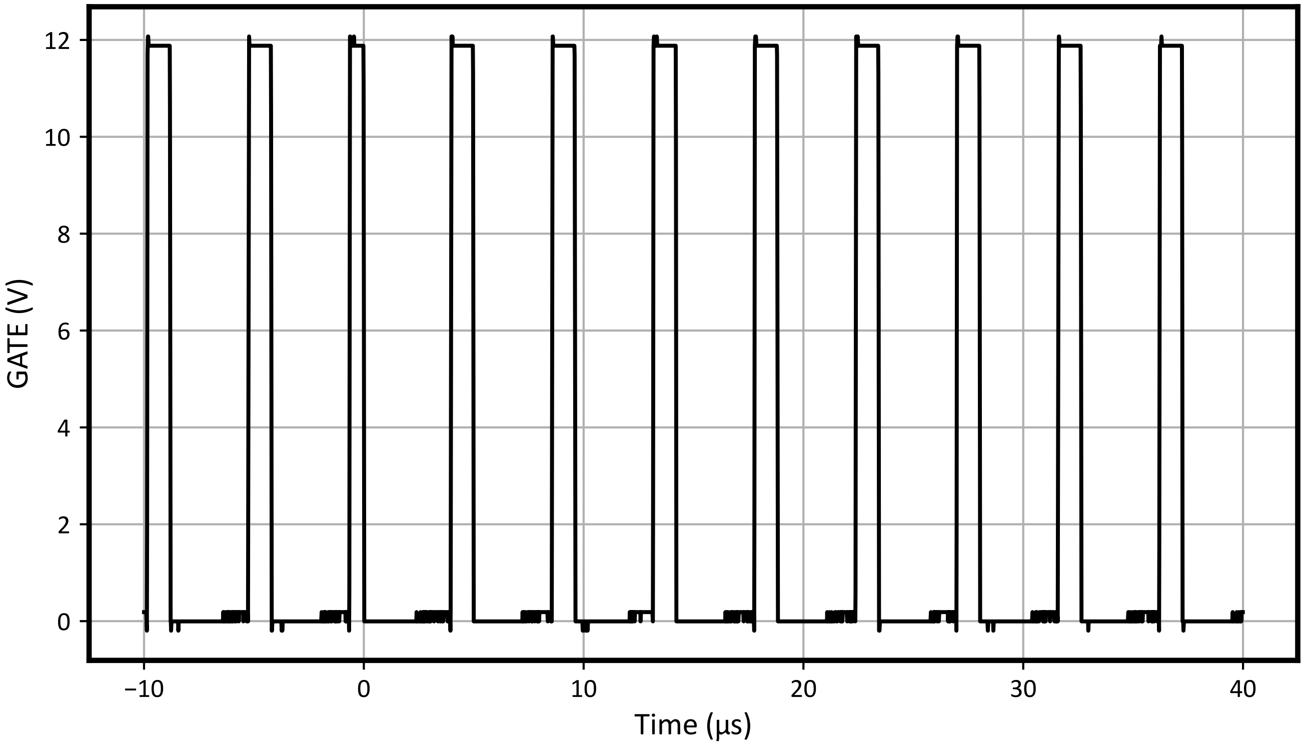


Figure 8-5. TPS7H5021-SP Silicon Mode GATE Pulse-Width Transient

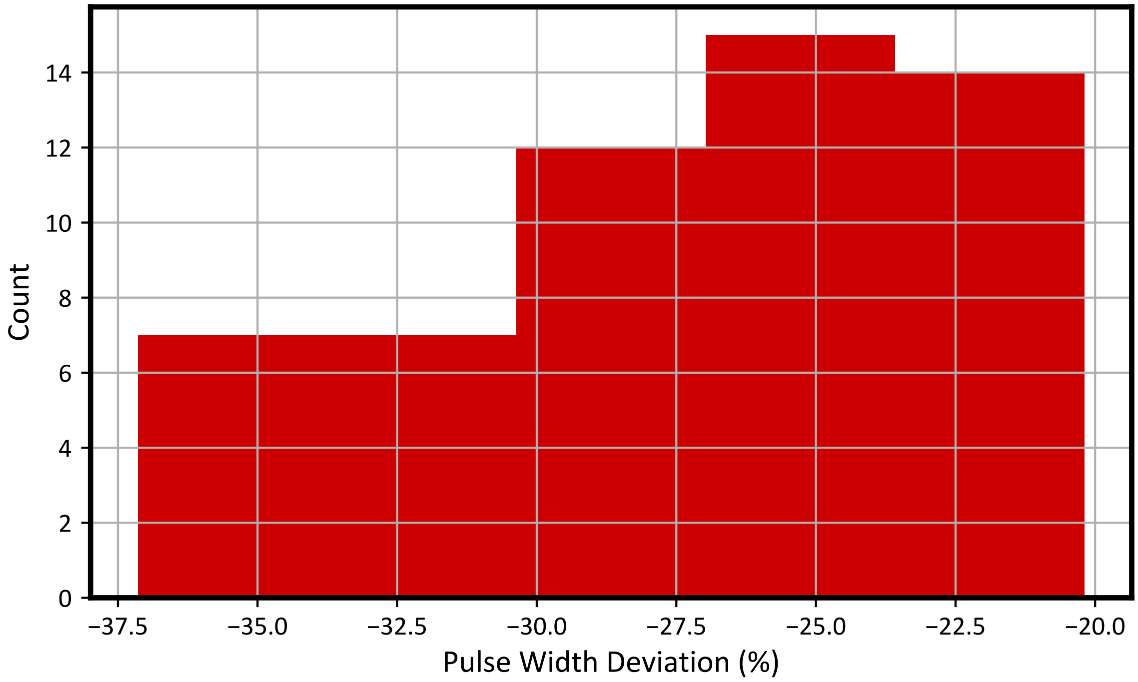


Figure 8-6. TPS7H5021-SP Silicon Mode GATE Pulse-Width Deviation Histogram

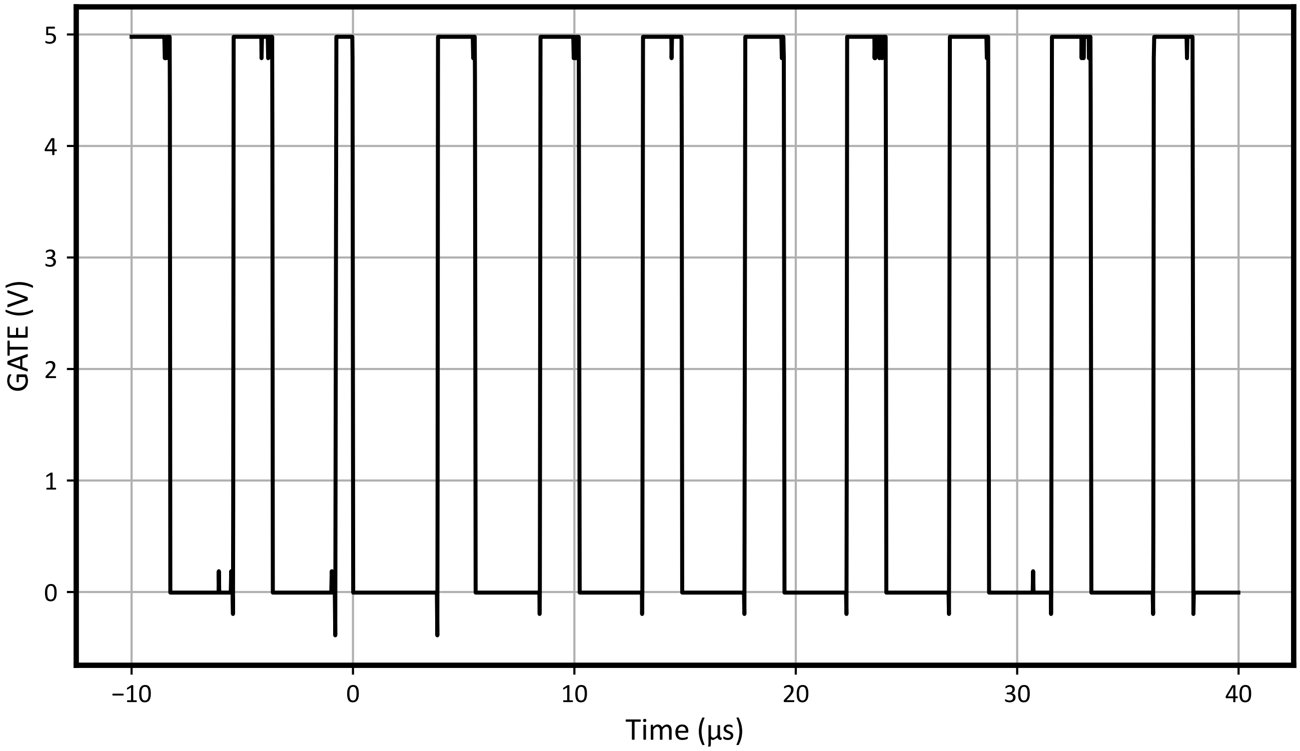


Figure 8-7. TPS7H5021-SP GaN Mode GATE Pulse-Width Transient

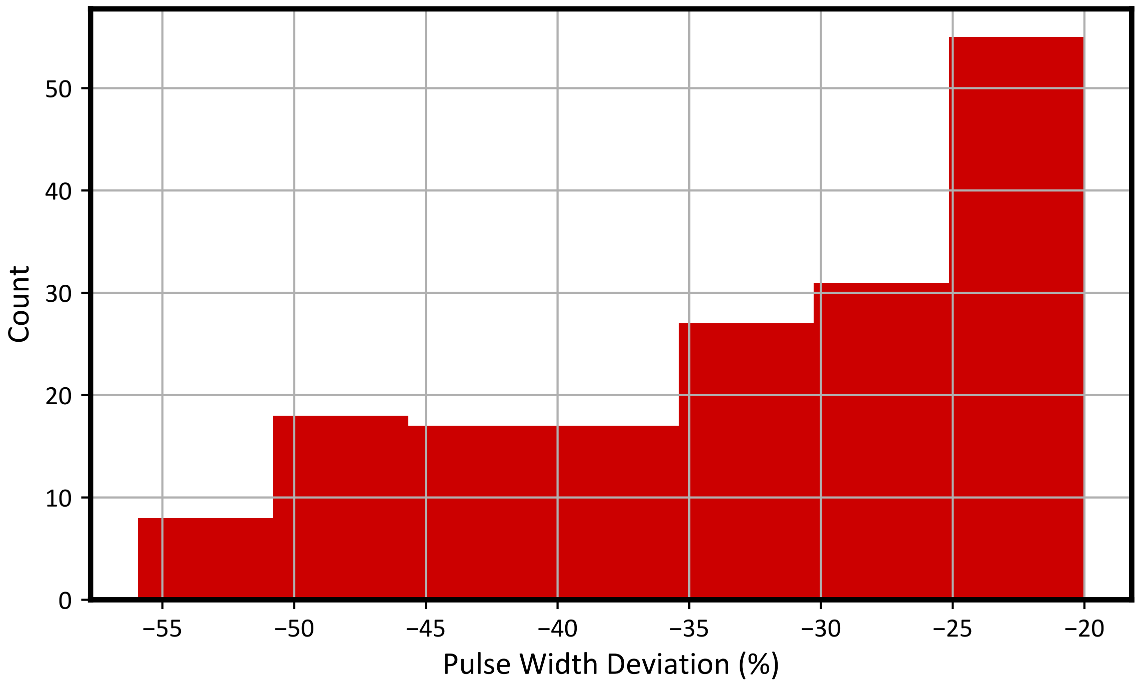


Figure 8-8. TPS7H5021-SP GaN Mode GATE Pulse-Width Deviation Histogram

Table 8-3. TPS7H502X-SP SET Cross-Sections

LET_{EFF} ($MeV \cdot cm^2/mg$)	Mode	Parameters	V_{IN} (V)	Fluence (ions/ cm^2)	# Transients	Upper-Bound Cross-Section (cm^2)
75	Silicon	100k	12	3×10^7	94	3.83×10^{-6}
		500k		8×10^7	421	5.79×10^{-6}
		1M		2×10^7	0	1.84×10^{-7}
	GaN	100k	4.5	3×10^7	191	7.34×10^{-6}
			12	2×10^7	89	5.48×10^{-6}
		500k	4.5	3×10^7	144	5.65×10^{-6}
			12	1×10^8	597	6.47×10^{-6}
		1M	4.5	5×10^7	3	1.75×10^{-7}
			12	2×10^7	10	9.20×10^{-6}
48	Silicon	500k	12	1×10^7	5	1.17×10^{-6}
	GaN	500k	12	1×10^7	44	5.91×10^{-6}

Flyback Configuration

To better understand functionality of the device closed-loop testing was conducted with the device in a flyback configuration. A flyback EVM was designed to allow the device to operate as a flyback converter with a power stage input voltage of 28V and an output voltage of 5V. During this testing TPS7H502X-SP was powered to operate in GaN mode with a nominal voltage of 12V at V_{IN} , P_{VIN} tied to V_{LDO} at 5V, and loaded to a 4A load on the output. The load was provided by a Chroma E-Load in constant resistance mode with a resistance of 1.25Ω. During the testing the GATE (OUTH and OUTL tied together before the transformer) signal and V_{OUT} (the DC output signal after the transformer) were monitored by a PXIe-5110 and PXIe-5172 respectively. Testing was done at room temperature at ^{165}Ho which produced a LET_{EFF} of 75MeV·cm^2/mg. During testing the PXIe-5110 scope was set to trigger if the signal exceeded |20%| from nominal using a pulse width trigger. For V_{OUT} the PXIe-5172 was set to trigger on a |3%| window. During all SET testing, there were three types of transients recorded on GATE that were all self-recoverable. The first was a long transient only seen during the beginning of the run when the beam shutter opened. The second was a greater than +20% pulse-width transient. The third was a less than -20% pulse-width transient. There were no transients observed on V_{OUT} during this testing indicating that the DC output of the flyback is transient free at the specified operating conditions at 75MeV·cm^2/mg.

Table 8-4. Summary of TPS7H502X-SP Flyback Configuration SET Test Conditions and Results

RUN #	UNIT #	V_{IN} (V)	Power Stage (V)	F_{SW} (Hz)	Load (A)	ION	LET_{EFF} (MeV·cm^2/mg)	FLUX (ions×cm^2/s)	FLUENCE (# ions)	#GATE ≥ |20%|	V_{OUT} # ≥ |3%|
79	18	12	28	500k	4	^{165}Ho	75	5.00×10^4	1.00×10^7	58	0
80	19	12	28	500k	4	^{165}Ho	75	5.00×10^4	1.00×10^7	49	0
81	20	12	28	500k	4	^{165}Ho	75	5.00×10^4	1.00×10^7	39	0
82	21	12	28	500k	4	^{165}Ho	75	5.00×10^4	1.00×10^7	48	0

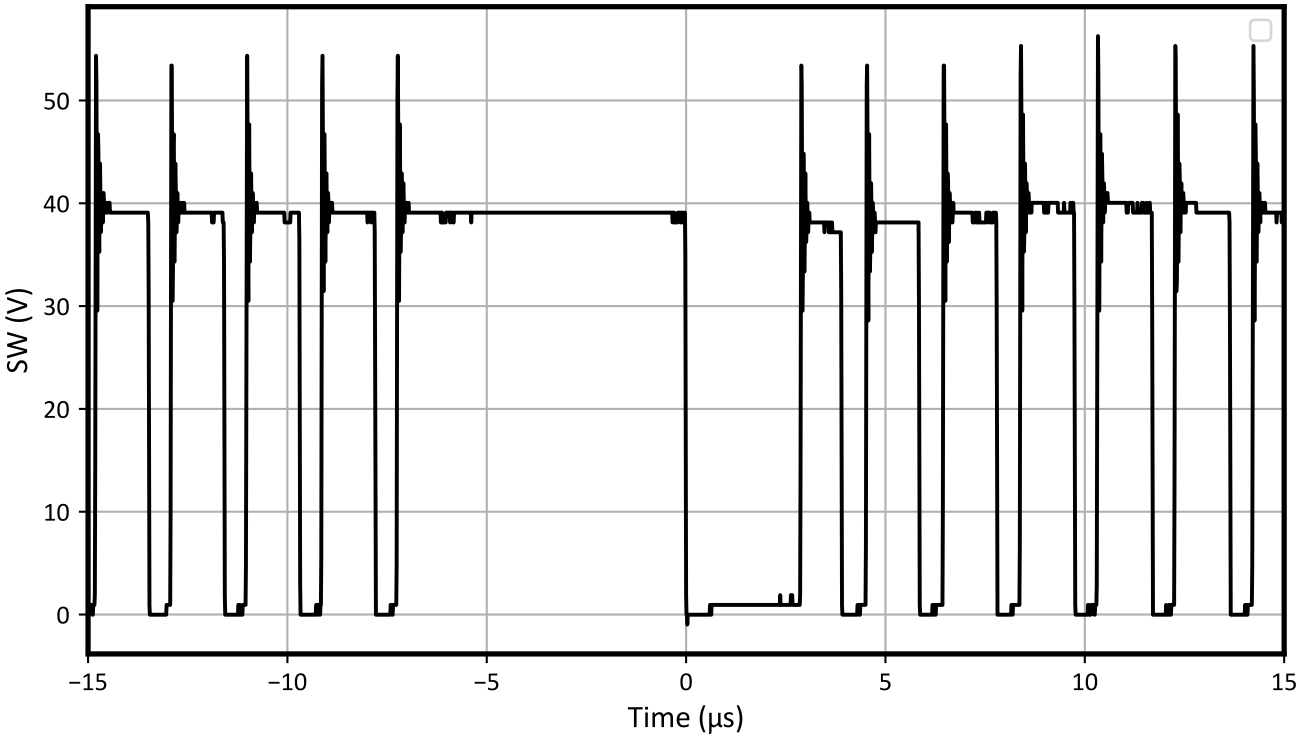


Figure 8-9. GATE transient during beam shutter open

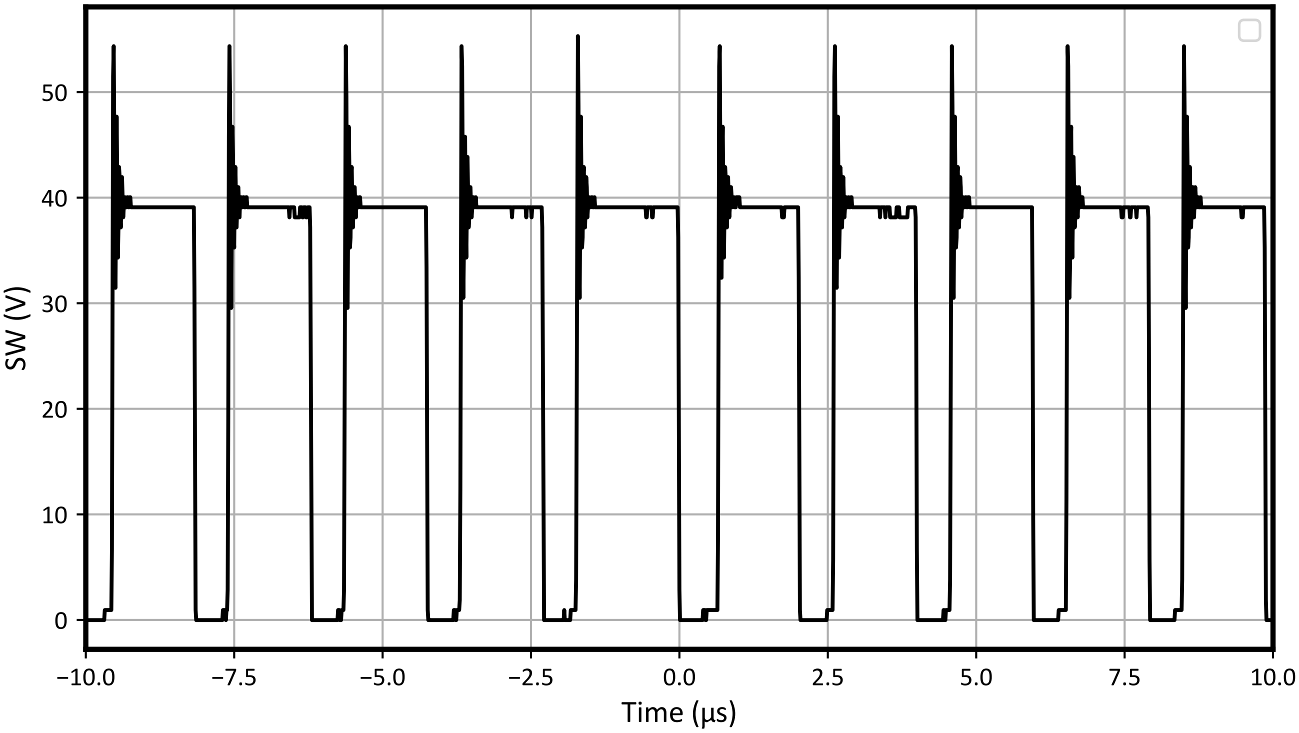


Figure 8-10. Typical Gate Transient >+20% Pulse-Width Deviation

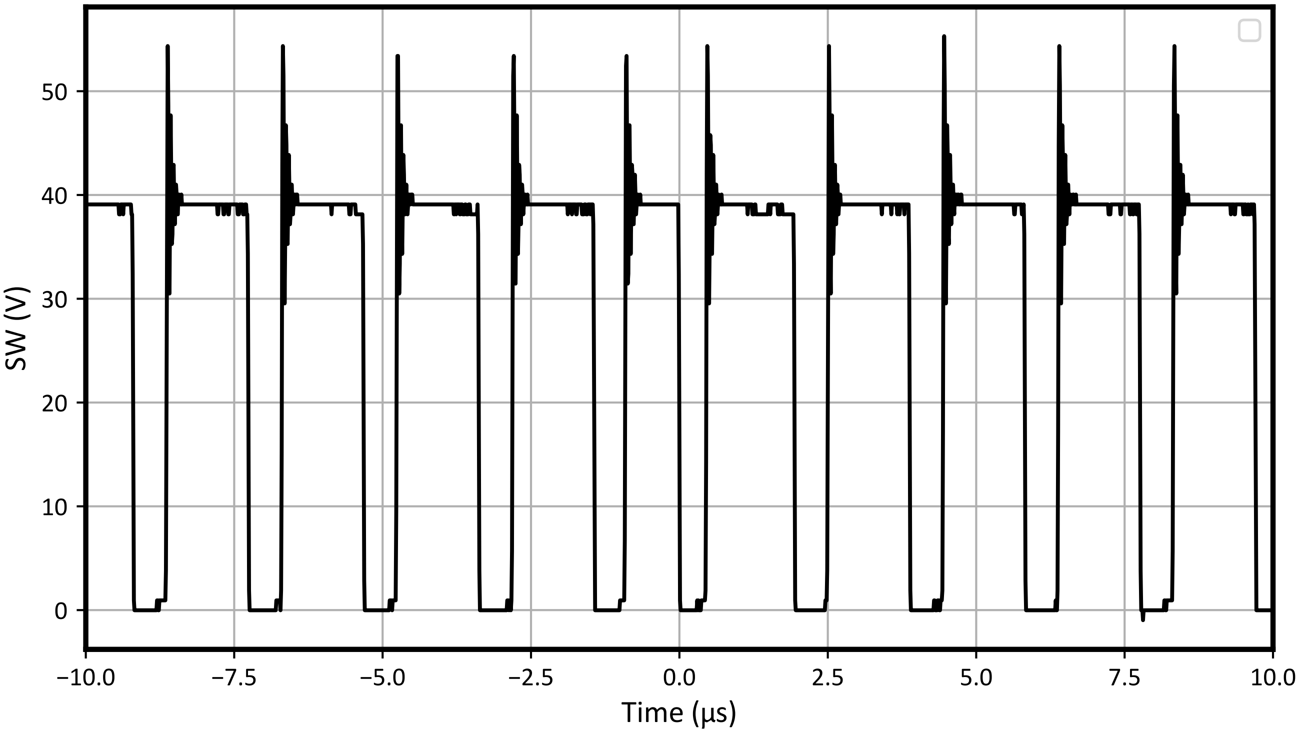


Figure 8-11. Typical Gate Transient < -20% Pulse-Width Deviation

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)	75	6.26×10^{-5}	2.84 x 10^{-8}	1.78×10^{-12}	7.40×10^{-5}	1.54×10^{9}
GEO		1.77×10^{-4}		5.02×10^{-12}	2.09×10^{-4}	5.46×10^{8}

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)	75	6.26×10^{-5}	1.42 x 10^{-8}	8.88×10^{-132}	3.70×10^{-5}	3.09×10^{9}
GEO		1.77×10^{-4}		2.51×10^{-12}	1.05×10^{-4}	1.09×10^{9}

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 TPS7H502X-SP radiation-hardness-assured, current mode, single-ended PWM controller with an integrated gate driver. Heavy-ions with LET_{EFF} = 75MeV·cm^2/mg were used for the SEE characterization campaign. Flux of ≈ 4x10^4 to 1x10^5 ions×cm^2/s and fluences of ≈ 1x10^7 ions/cm^2 per run were used for the characterization. The SEE results demonstrated that the TPS7H502X-SP is free of destructive SEL and SEB LET_{EFF} = 75MeV·cm^2/mg and across the full electrical specifications. Transients at LET_{EFF} = 75MeV·cm^2 /mg were monitored and discussed CREME96-based worst week event-rate calculations for LEO(ISS) and GEO orbits for DSEE are presented for reference.

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