Radiation Report

Single-Event Effects Test Report of the DP83561-SP Space Grade (QMLV-RHA) 10/100/1000 Ethernet PHY

TEXAS INSTRUMENTS

ABSTRACT

The purpose of this study is to characterize the single-event-effect (SEE) performance due to heavy-ion irradiation of the DP83561-SP. Heavy-ions with LET_{EFF} ranging from 8 to 121 MeV × cm^2/ mg were used to irradiate production RHA devices in the experiments with fluences up to 10^6. The results demonstrated that the DP83561-SP is SEL-free up to 121 MeV × cm^2/ mg at T = 125°C. The SET cross section and BER calculations are presented across different LETs.

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1 Introduction

The DP83561-SP is a high reliability gigabit ethernet PHY designed for the high-radiation environment of space. The DP83561-SP is a low power, fully featured physical layer transceiver with integrated PMD sub-layers to support 10BASE-Te, 100BASE-TX and 1000BASE-T Ethernet protocols. The DP83561-SP is designed for easy implementation of 10/100/1000Mbps Ethernet LANs in extremely hostile environments. The device interfaces to twisted pair media through an external transformer. This device interfaces to the MAC layer through Reduced GMII (RGMII) and MII. The following are some of the device features:

- QML Class V (QMLV), RHA, SMD 5962-20216
- Military temperature range: –55°C to 125°C
- Radiation performance
  - RHA up to TID = 100krad(Si)
  - SEL Immune to LET = 121MeV× cm^2 / mg
  - SEE Characterized to LET = 85MeV × cm2 /mg
- Single Event Functional Interrupt (SEFI) monitor suite – monitor
  - IEEE PCS state machine monitors
  - ECC configuration register monitor
  - PLL lock monitor
  - On-chip temperature monitor
  - Pin-configurable automatic SEFI recovery
- Fully compatible to IEEE802.3 1000BASE-T, 100BASE-TX and 10BASE-Te specifications
- Low RGMII latency (Tx < 90ns, Rx < 290ns)
- MAC interface: RGMII, MII

See the DP83561-SP Data Sheet for the full list of device features.

The device is Radiation Hardened by Design (RHBD), fabricated by Texas Instruments using a CMOS process, and is available in 64-pin Ceramic Quad Flat Pack (CQFP) package, with a 11mm × 11mm body size (nominal). Visit the DP83561-SP product page for more detailed technical specifications, user's guides, and application notes.

Table 1-1. Overview Information

DESCRIPTION (1)	DEVICE INFORMATION (1)
TI Part Number	DP83561-SP
Orderable Name	5962021601VXC
Device Function	Ethernet PHY Transceiver
Technology	Ethernet
Exposure Facility	Radiation Effects Facility, Cyclotron Institute, Texas A&M University
Irradiation Temperature	25°C and 125°C (For SEL Testing)

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2 Single-Event Effects

With deployment of Ethernet devices to space systems, the need for PHYs to be radiation hardened by design for high performance and reliability is becoming more important. This document discusses SET and SEL performance of the DP83561-SP.

SEL can occur if excess current injection caused by the passage of an energetic ion is high enough to trigger the formation of a parasitic cross-coupled PNP and NPN bipolar structure (formed between the p-substrate and n-well and n+ and p+ contacts) [1, 2]. If formed, the parasitic bipolar structure creates a high-conductance path (creating a steady-state current that is orders-of-magnitude higher than the normal operating current) between the power and ground that persists (is *latched*) until power is removed or until the device is destroyed by the high-current state. The design and process techniques used on the DP83561-SP for SEL-mitigation were sufficient as the DP83561-SP exhibited no SEL events with heavy-ions of up to LET_{EFF} = 121MeV × cm^2/ mg at a flux of 10^5 ions / cm^2·s, fluences in excess of 10^7 ions/cm^2, and an ambient temperature of 125°C.

3 Test Device and Evaluation Board Information

The DP83561-SP is packaged in a 64-pin, thermally-enhanced, dual-ceramic, flat pack package (CQFP) as shown in Figure 3-1. The DP83561EVM evaluation board was used to evaluate the performance and characteristics of the DP83561-SP under heavy-ions. Figure 3-3 shows the top views of the evaluation board used for the radiation testing. Refer to the DP83561EVM User Guide for the evaluation board schematics and layout design.

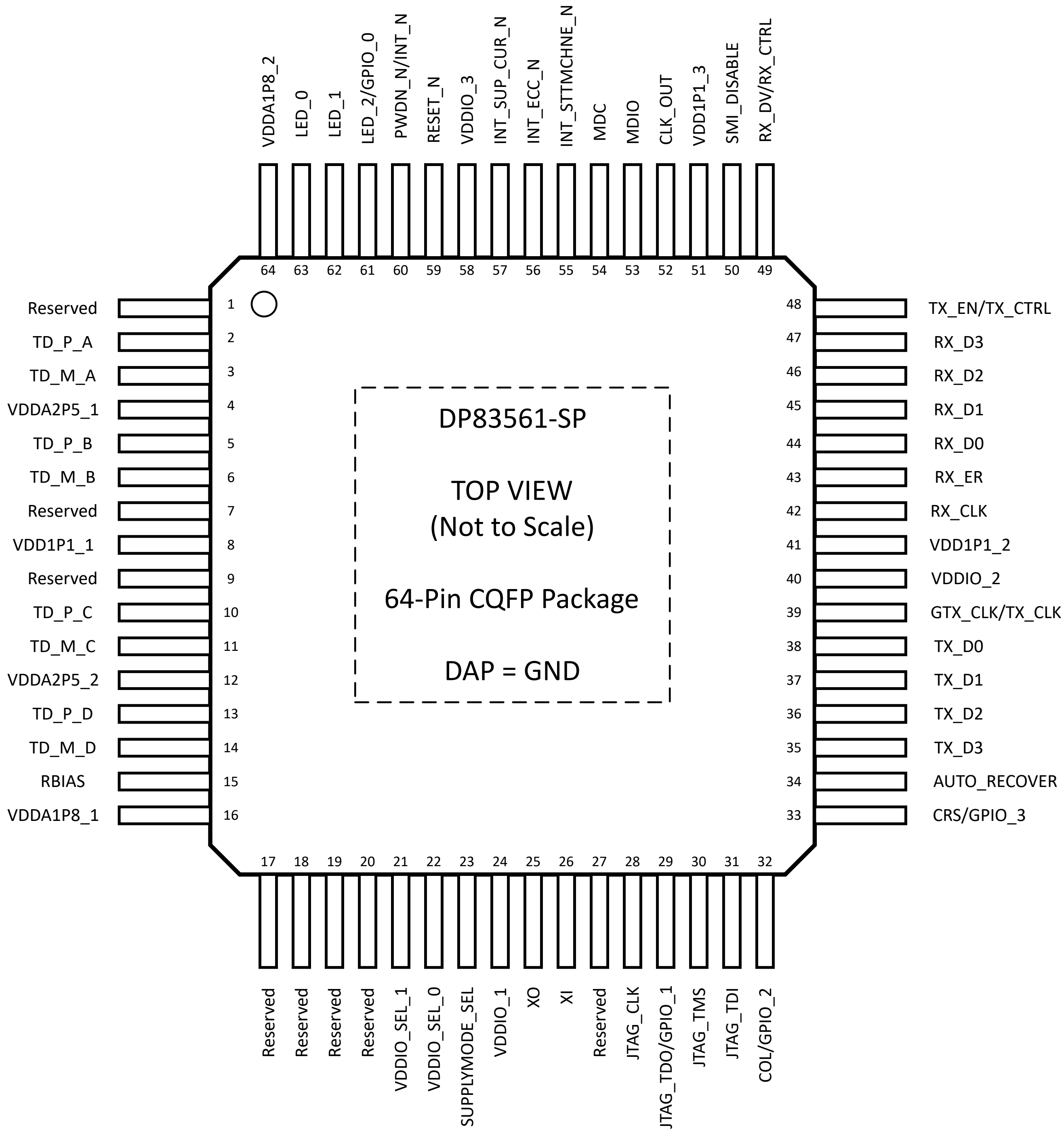
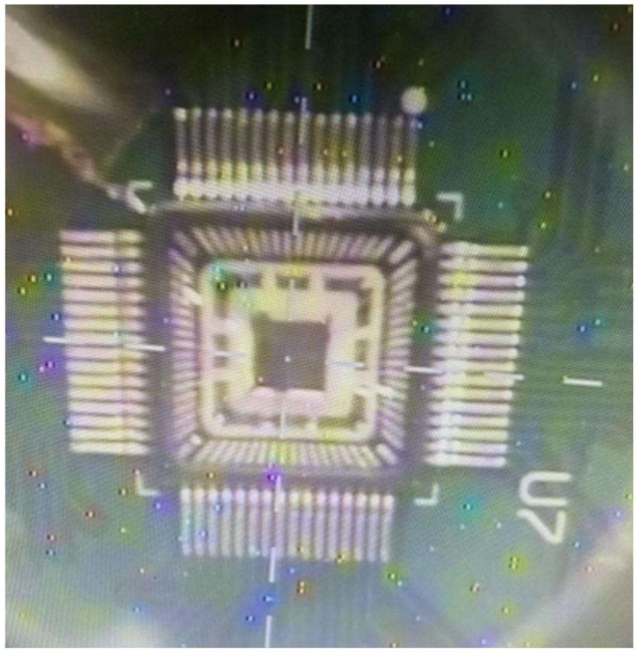


Figure 3-1. HBE Package 64-Pin CQFP Top View



The package lid was removed to reveal the die face for all heavy ions testing.

Figure 3-2. Photograph of Pin Out Diagram [Top] and Delidded DP83561-SP [Bottom]

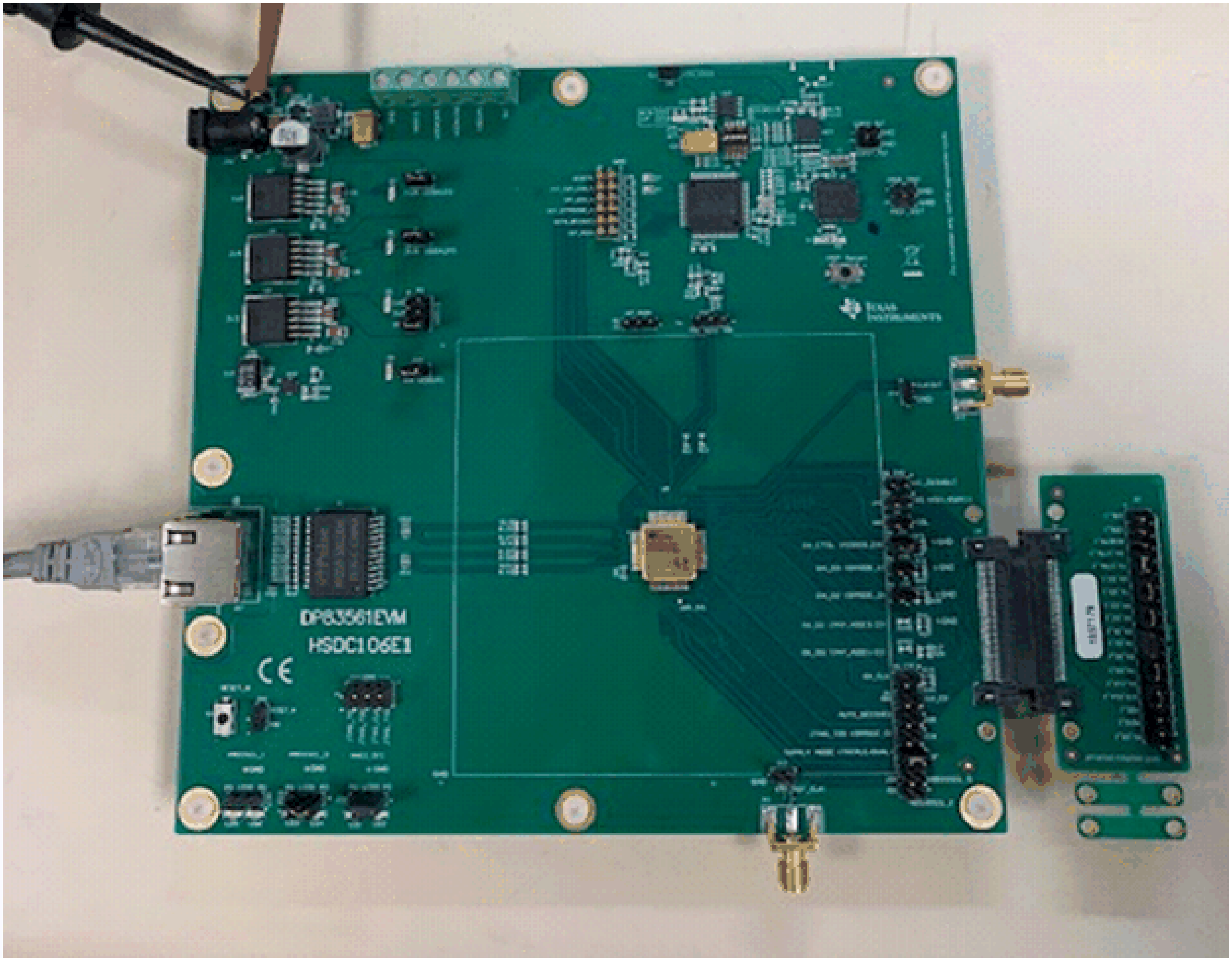


Figure 3-3. DP83561-SP Board Top View with MAC Interface Breakout Board

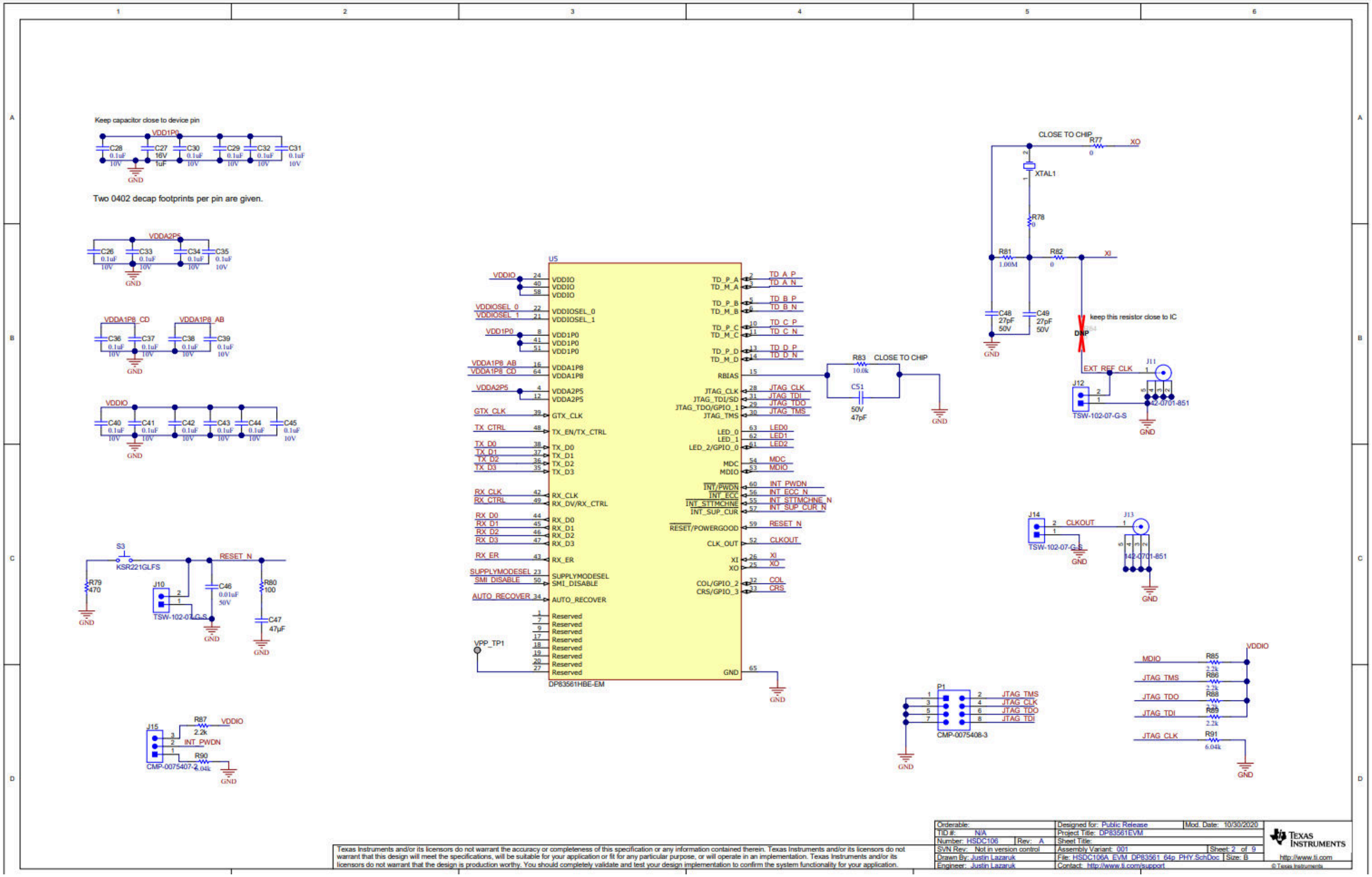


Figure 3-4. DP83561EVM Main Block Schematic

4 Irradiation Facility and Setup

The heavy-ion species used for the SEE studies on this product were provided and delivered by the TAMU Cyclotron Radiation Effects Facility [6] 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 one inch diameter circular cross sectional area for the in-air station. Uniformity is achieved by magnetic defocusing. The flux of the beam is regulated over a broad range spanning several orders of magnitude. For the bulk of these studies, ion flux of 10^4 and 10^5 ions/cm^2·s were used to provide heavy-ion fluences of 10^6 and 10^7 ions/cm ^{2}.

For the experiments conducted on this report, ^{40}Ar ions at angle of 39.4° of incidence were used for an LET_{EFF} of 8MeV × cm^2/ mg, ^{197}Au ions at angles of 0° and of incidence were used for an LET_{EFF} of 85 and 95MeV·cm^2/mg. Also, ^{197}Au ions at angles of 29° and 43° of incidence were used for an LET_{EFF} of 100 and 121MeV × cm^2/mg, respectively. ^{131}Xe at angles of 0° and 39.4° of incidence were used for an LET_{EFF} of 48 and 78MeV × cm^2/mg, respectively.

Figure 4-1 shows the DP83561-SP test board used for the experiments at the TAMU facility. 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. Test points were soldered on the back for easy access of the signals while having enough room to change the angle of incidence and maintaining the 40mm distance to the die. The air gap between the device and the ion beam port window was maintained at 40mm for all runs.

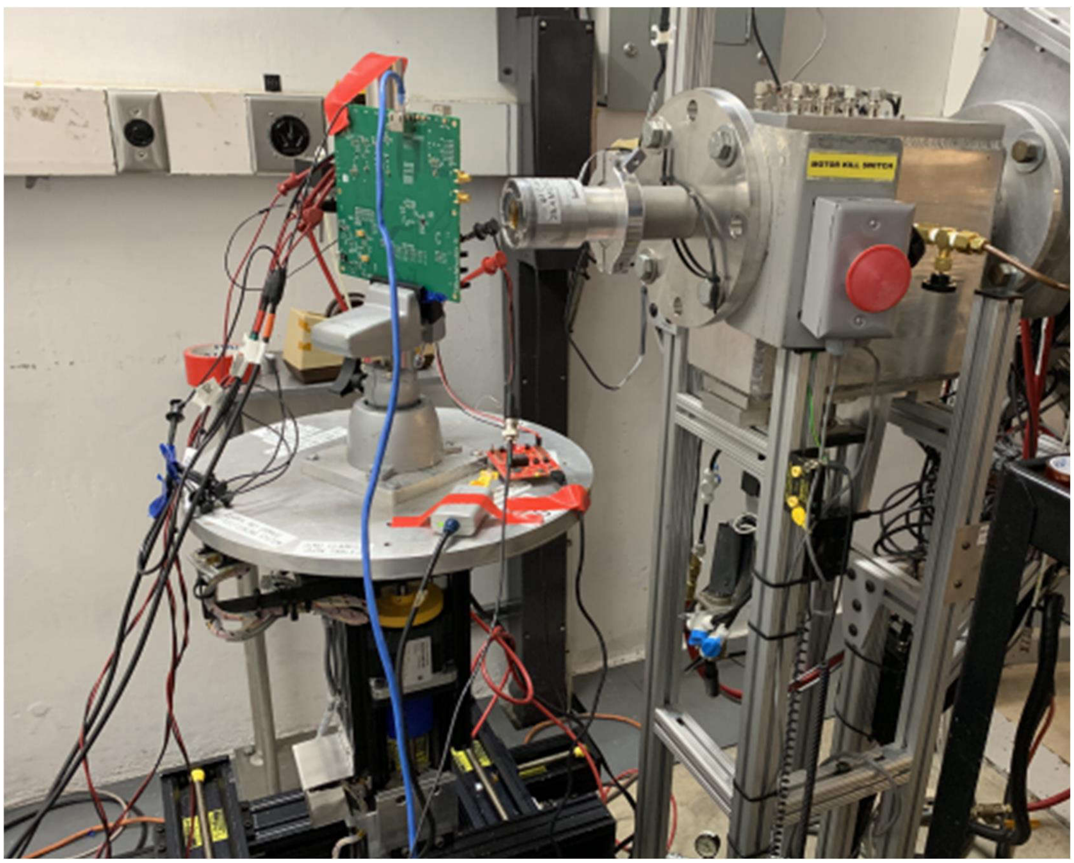


Figure 4-1. Photograph of the DP83561-SP Mounted on the DP83561EVM in Front of the Heavy Ion Beam Exit Port at the TAMU Accelerator Facility

A Spirent Smartbits SMB-200 packet generator was used to generate Ethernet packets to the DP83561-SP on the DP83561EVM. The DP83561EVM was configured for external RGMII loopback, using an external breakout board to short the MAC receive pins to the MAC transmit pins of the DP83561-SP device. Packets were returned through the PHY back to the Smartbits packet generator, where total number of packets sent, packets received, and CRC errors were counted. Additional signals, link status and RX_CLK, were monitored as well.

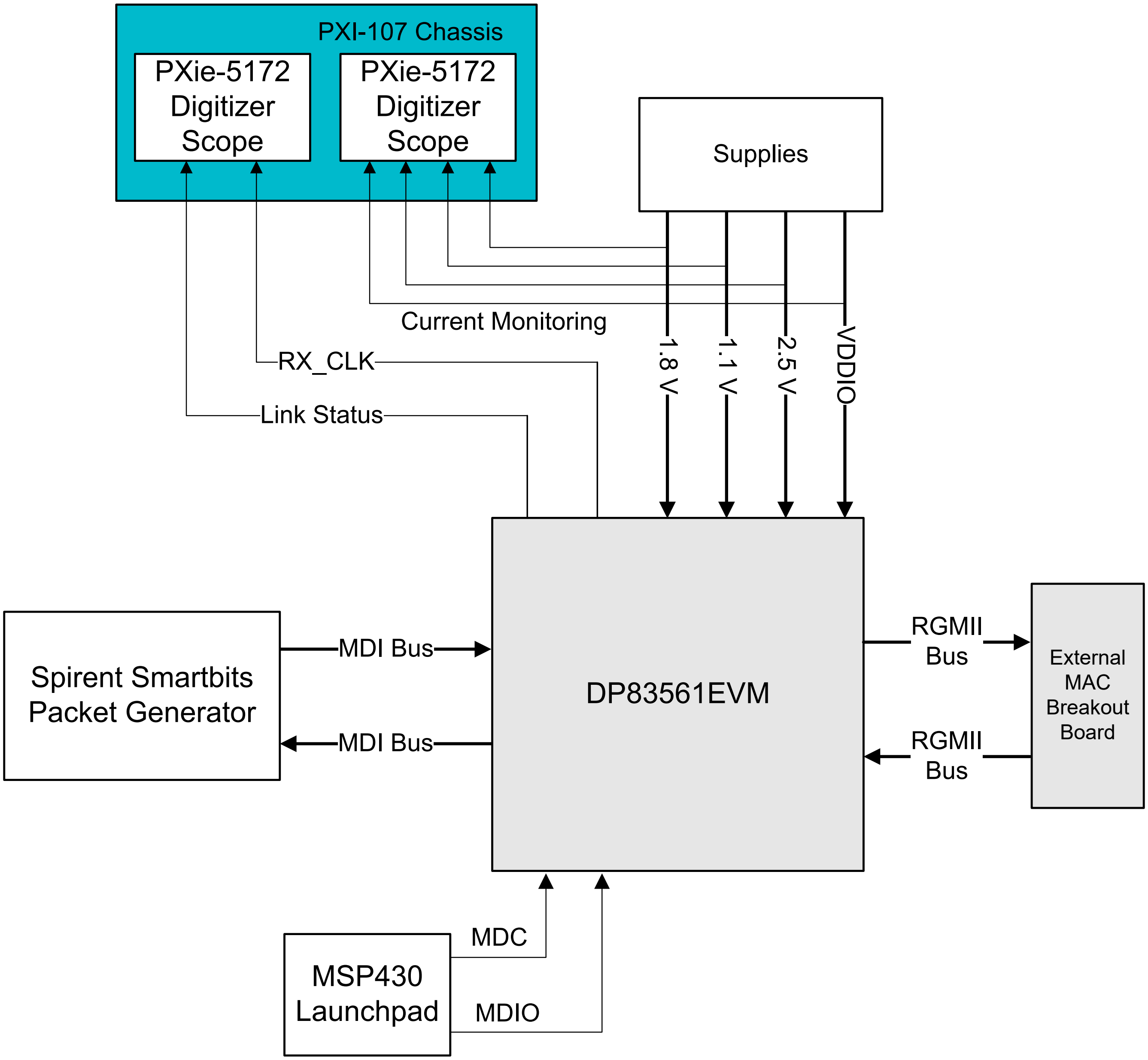


Figure 4-2. DP83561-SP Radiation Test Setup Block Diagram

5 Depth, Range, and LET_{EFF} Calculation

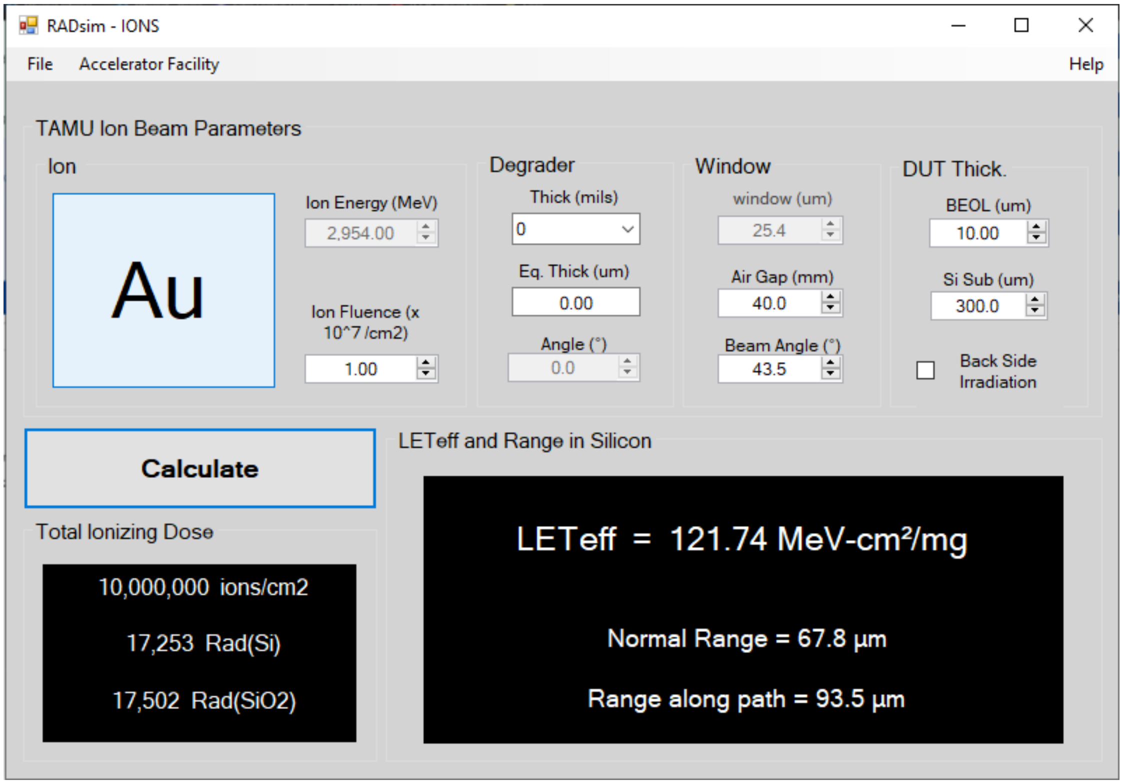


Figure 5-1. GUI of RADsim Application (Right) Used to Determine Key Ion Parameters

The DP83561-SP is fabricated in the TI Linear BiCMOS 65-nm process with a back-end-of-line (BEOL) stack consisting of three levels of standard thickness aluminum metal on a 0.6µm pitch and a fourth level of thick aluminum. Accounting for energy loss through the 1mil thick Aramica (Kevlar®) beam port window, the 40mm air gap, and the BEOL stack over the DP83561- SP, the effective LET (LET_{EFF}) at the surface of the silicon substrate and the depth and ion range was determined with the custom RADsim-IONS application (developed at Texas Instruments and based on the latest SRIM2013 [7] models). Table 5-1 shows the results. The stack was modeled as a homogeneous layer of silicon dioxide (valid since SiO_2 and aluminum density is similar).

Table 5-1. Argon, Gold, and Xenon Ion LET_{EFF}, Depth, and Range in Silicon

ION TYPE	ANGLE OF INCIDENCE (°)	DEPTH OF SILICON (µm)	RANGE OF SILICON (µm)	LET_{EFF} (MeV × cm^2 /mg)
^{197}Au	43	x	x	121
^{197}Au	29	x	x	100
^{197}Au	0	x	x	85
^{131}Xe	39.4	x	x	78
^{131}Xe	0	x	x	48
^{40}Ar	39.4	x	x	8

6 Test Setup and Procedures

SEE testing was performed on a DP83561-SP device mounted on a DP83561EVM. The device power was provided by using terminal block J17. For the SEL and SET testing, the device was powered up to the maximum recommended supply voltages for each supply. Ambient temperature was measured to be 125 degrees Celsius, monitored using thermocouple on the board for both 1000Mbps, and 100Mbps configuration.

- VDDIO set to 3.465V
- VDD1P1 set to 1.155V
- VDD2P5 set to 2.65V
- VDD1P8 set to 1.89V

Supply currents were dynamically monitored throughout all tests. No incidences of SEL were detected on any ion runs. A single high current was observed during the 100Mbps SEL testing. However, this current value can be attributed to the PHY re-setting to a Gigabit speed when experiencing the high flux and fluence rate. The Gigabit speed setting was confirmed by monitoring the RX_CLK frequency, and the high current observed did not exceed the expected current for Gigabit communication. Link status, and packet transmission were also dynamically monitored through GPIOs and the Smartbits.

All boards used for SEE testing were fully checked for functionality. Dry runs were also performed to verify that the test system was stable under all bias and load conditions prior to being taken to the TAMU facility. During the heavy-ion testing, the LabView control program powered up the DP83561-SP device and set the external sourcing and monitoring functions of the external equipment. After functionality and stability had been confirmed, the beam shutter was opened to expose the device to the heavy-ion beam. The shutter remained open until the target fluence was achieved (determined by external detectors and counters). During irradiation, the PXIe-5101 scope cards continuously monitored the signals. When the output voltage exceeds the pre-defined 3% window trigger, or when the PG signal changed from High to Low (using a negative edge trigger), a data capture was initiated on the scope cards. 20k samples were recorded with a pre-defined 20% reference. No sudden increases in current were observed (outside of normal fluctuations) on any of the test runs indicated that no SEL events occurred during any of the tests.

7 Single Event Effects (SEE)

7.1 Single-Event-Latchup (SEL)

SEL characterizations was performed with ambient temperature of 125°C. Ambient temperature of 125°C was achieved with a convection heat gun aimed at the die. The ambient temperature was monitored during the testing using a K-Type thermocouple attached to the heat slug of the package with solder paste. Thermocouple and die correlation was verified by using a thermal IR camera prior to reaching the heavy-ions facility (TAMU). The device was exposed to a Gold (Au) heavy-ion beam incident on the die surface at different angles for a LET_{EFF} from 85MeV·cm^2/mg up to 121MeV·cm^2/mg across multiple runs. Flux of approximately 10^5 ions/cm^2 ·s and fluence of $1×10^7$ ions/cm^2 were used. Run duration to achieve this fluence was approximately two minutes. As mentioned in Section 6, all supplies were set to the maximum allowable value.

For SEL characterization, the PHY was first initialized for communication at the proper speed, and to configure the LEDs for link indication. Link status was monitored throughout the beam run. PHY register values were recorded prior to the run. During the run, link was lost, as expected, and was recovered post run. Link recovery did not require a power cycle, but sometimes required a soft reset through registers, a hard reset through registers, or a hard reset through grounding the reset pin through hardware. Under this condition (no power cycle required), no incidences of SEL were detected on any ion runs, indicating that the DP83561-SP is SEL-immune up to LET_{EFF} = 121 MeV × cm^2/ mg at 125°C. A single high current event was observed during one of the runs while testing 100Mbps mode, though RX_CLK was also observed to produce a clock frequency of 125MHz. The high current value observed matched the expected current for 1G communication, and the RX_CLK frequency of 125MHz confirm that the device had been momentarily reset for 1G mode, before recovering to a 100Mbps mode of operation. The device could be re-programmed back to the 100Mbps mode and the device currents were normal Indicating the current fluctuation is caused by register change.

Table 7-1 summarizes the SEL test conditions, including LET_{EFF}, MAC interface mode, and speed, as well as the overall results. To reiterate, no incidences of SEL were detected on any ion runs, indicating that the DP83561-SP is SEL-immune up to LET_{EFF} = 121MeV·cm^2/mg at 125°C. The SEL cross section was calculated based on zero events observed using a 95% (2σ) confidence interval. Figure 7-1 shows a typical current plot.

$\sigma_{SEL} \leq 7.38 \times 10^{-8}$ cm^2/device LET_{EFF} = 121 MeV × cm^2/ mg, at 125°C, 95% confidence.

Table 7-1. Summary of DP83561-SP SEL Results Across Speeds and MeV Levels

TEMP (°C)	ION	ANGLE OF INCIDENCE (°)	LET_{EFF} (MeV·cm^2/mg)	FLUX (IONS/CM^2·s)	FLUENCE (IONS/CM^2)	MAC - MDI CONFIGURATION	CURRENT (mA)				SEL EVENTS
							VDD1P1 (1.21)	VDD1P8 (1.89)	VDDA2P5 (2.62)	VDDIO (3.45)	
125	Au	43	121	$1.00×10^5$	$1.00×10^7$	RGMII - 1G	182	56.08	90.05	56	0
125	Au	29	100	$1.00×10^5$	$1.00×10^7$	RGMII - 1G	181.2	56.07	90.09	58	0
125	Au	0	85	$1.00×10^5$	$1.00×10^7$	RGMII - 1G	180.7	56	90.3	58	0
125	Au	0	85	$1.00×10^5$	$1.00×10^7$	RGMII - 1G	180.9	55.9	90.6	58	0
125	Au	0	85	$1.00×10^5$	$1.00×10^7$	RGMII - 100M	85.5	22.2	47.2	33	0

MII is characterized up-to 85 LET due to limited time at Lab. We expect it to meet similar levels as 1G

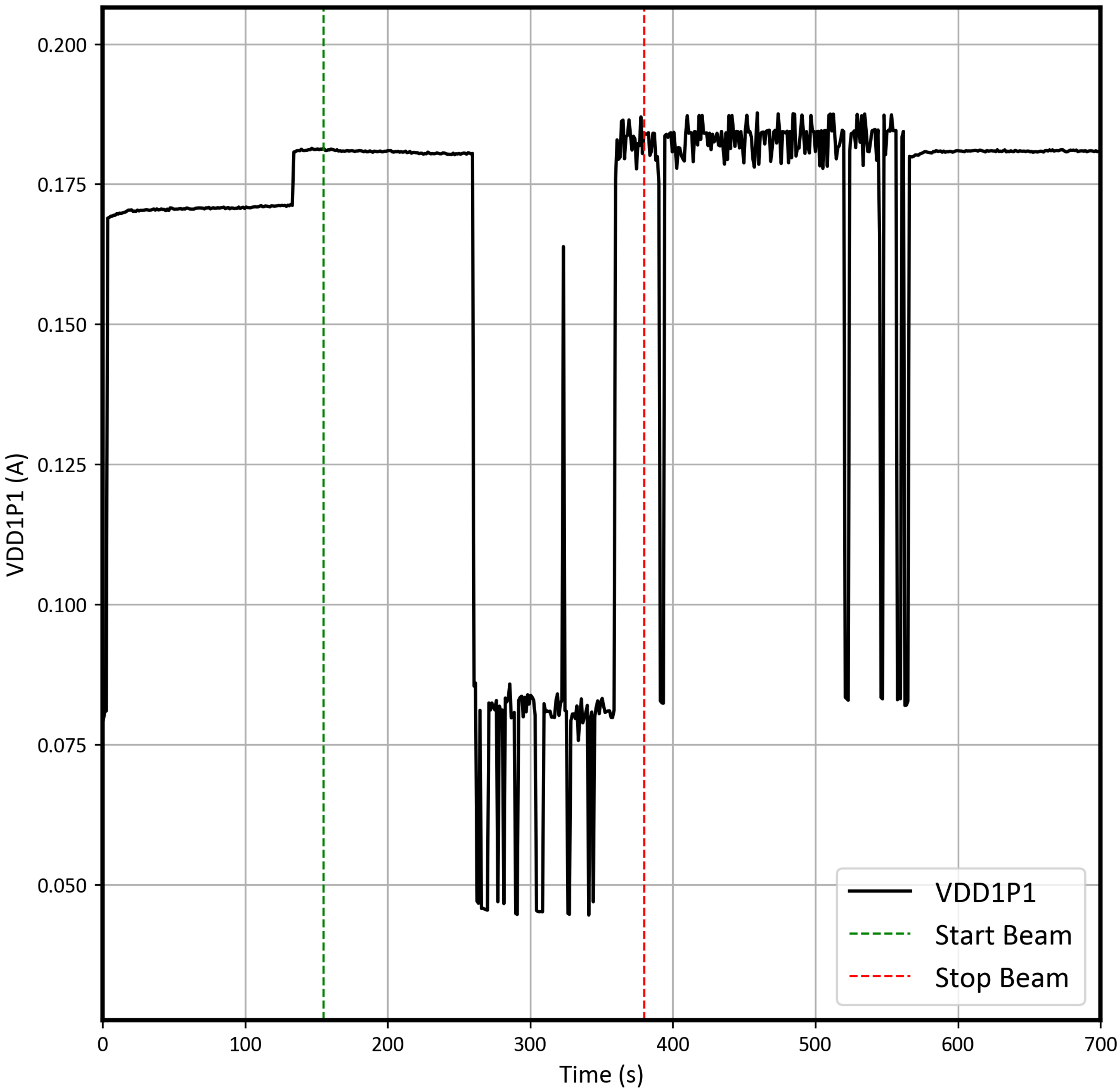


Figure 7-1. Current Versus Time for VDD1P1 SEL Run #4 at T = 125°C and 121 MeV·cm^2/mg

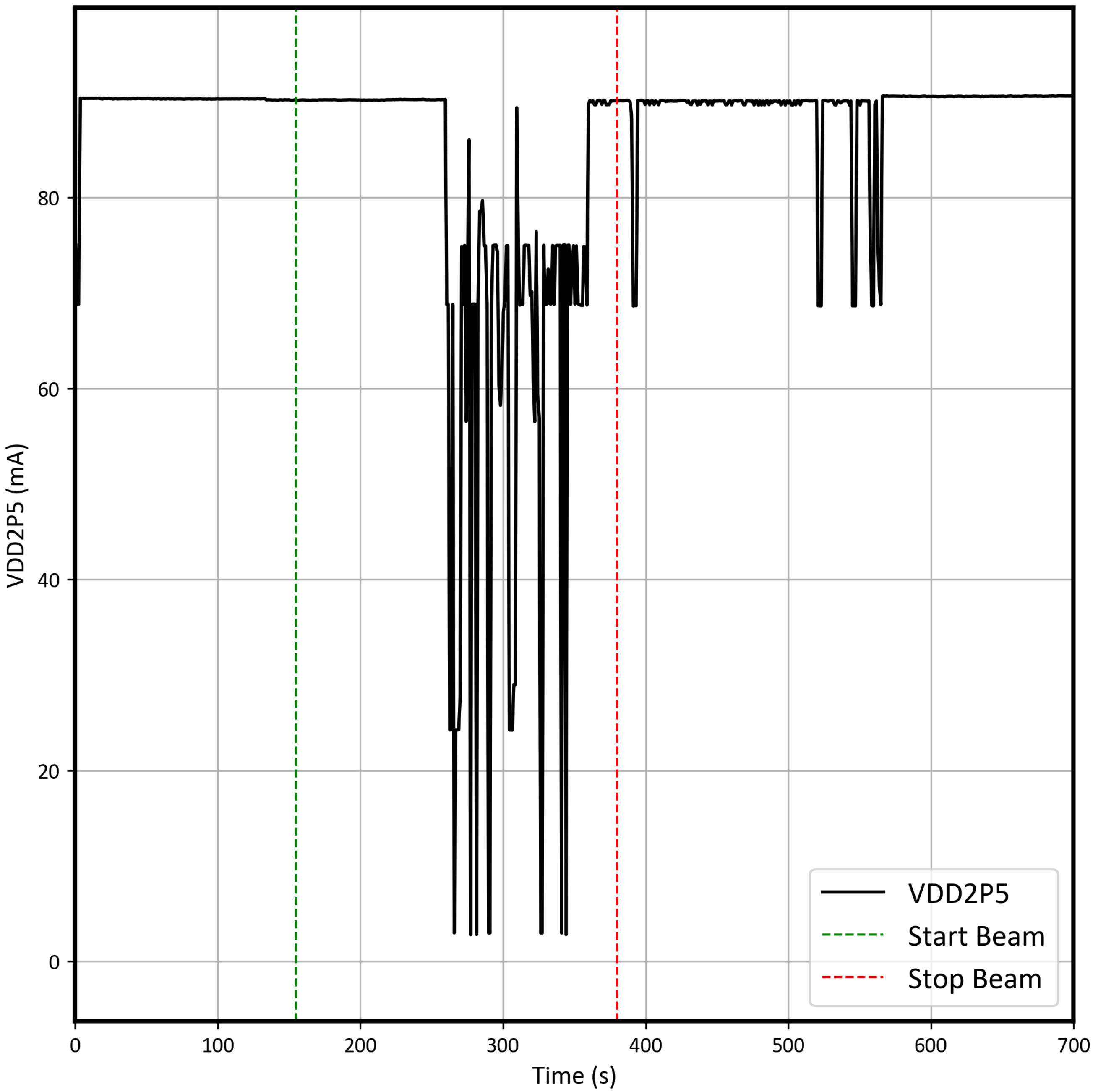


Figure 7-2. Current Versus Time for VDD2P5 SEL Run #4 at T = 125°C and 121 MeV·cm^2/mg

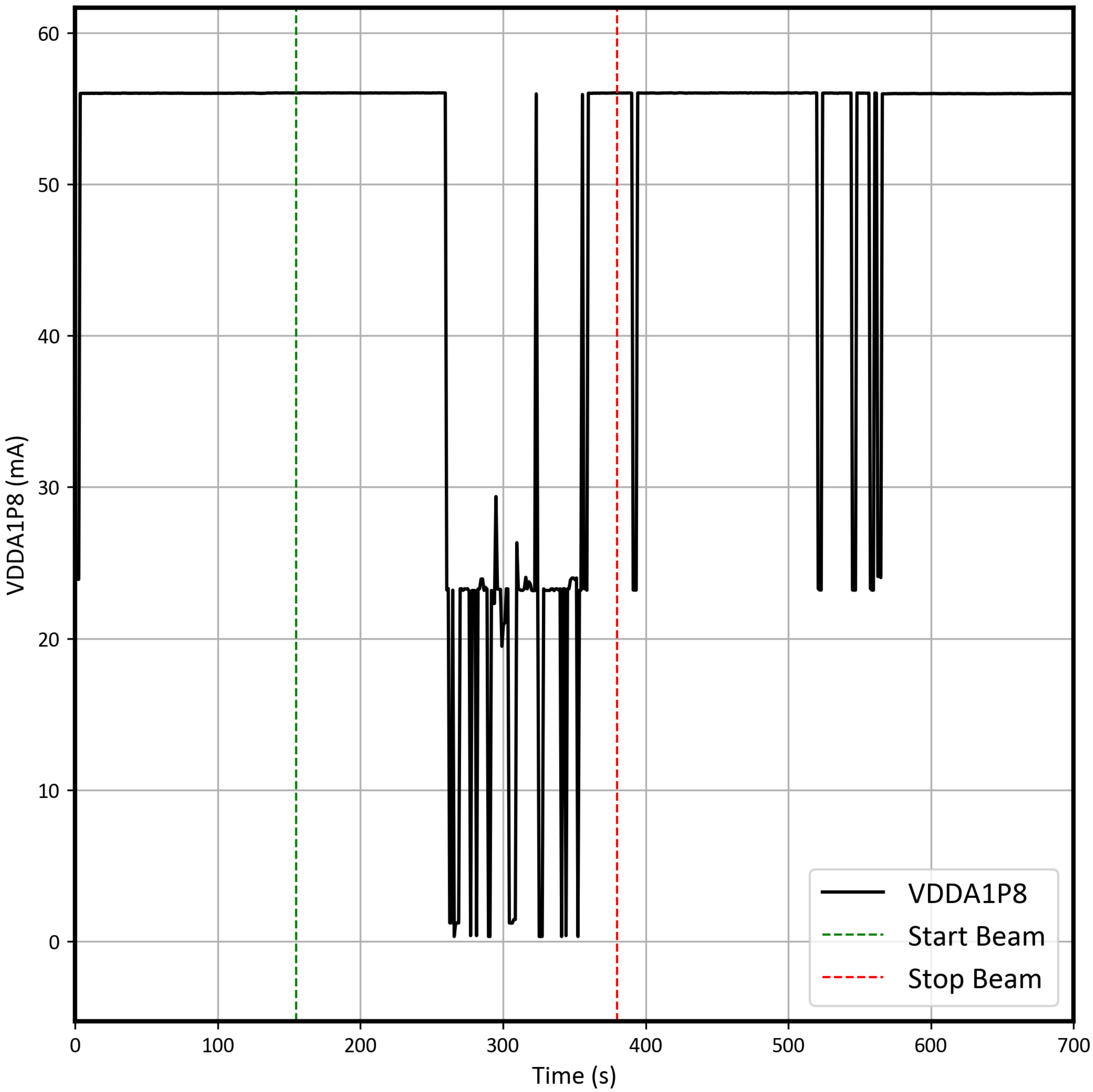


Figure 7-3. Current Versus Time for VDDA1P8 SEL Run #4 at T = 125°C and 121 MeV·cm^2/mg

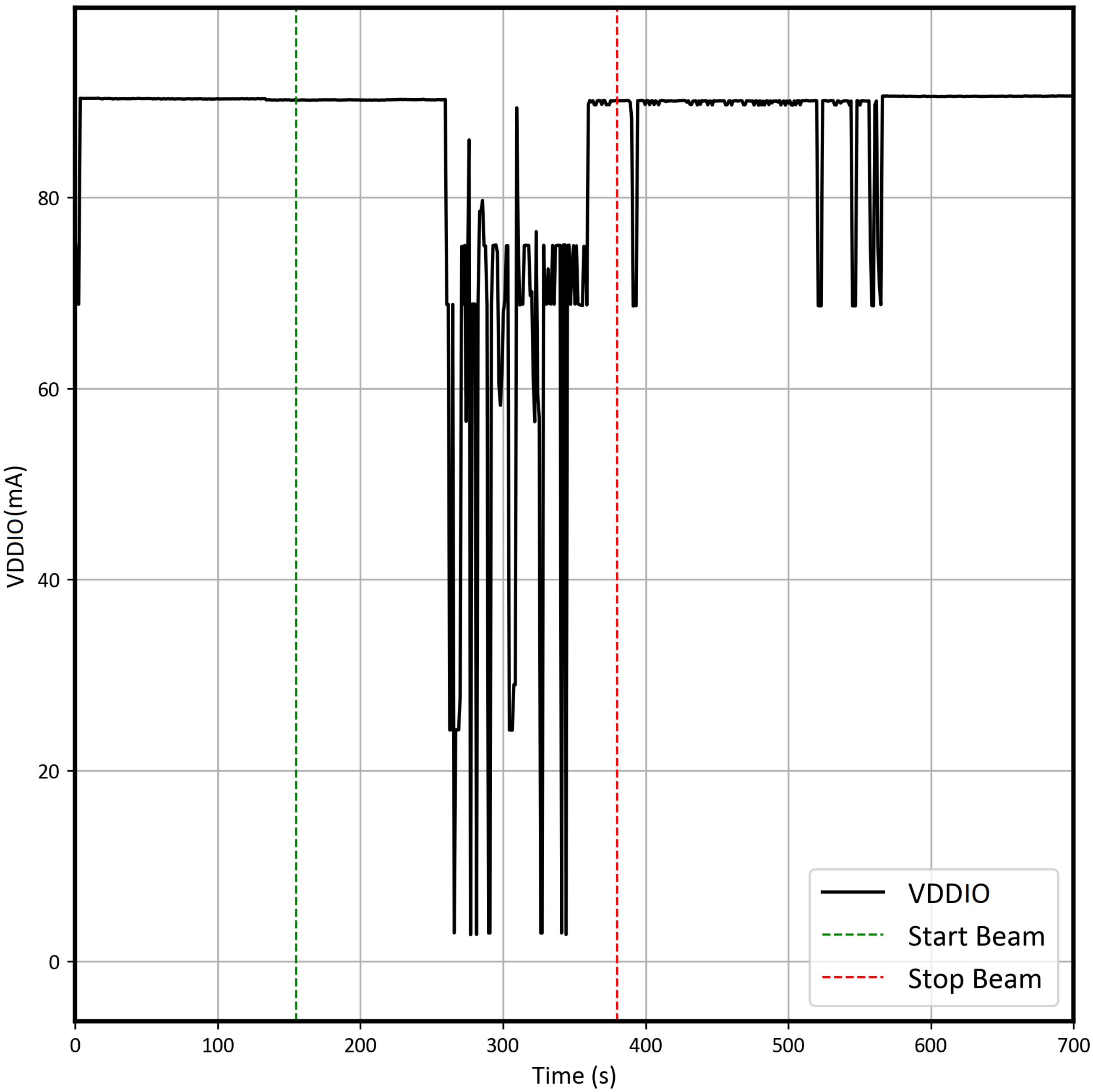


Figure 7-4. Current Versus Time for VDDIO SEL Run #4 at T = 125°C and 121 MeV·cm^2/mg

7.2 Single Event Transients (SET)

SET testing was performed at room temperature, at three different LETeff levels, 8MeV, 48MeV, and 85MeV. With ^{197}Au ions at an angle of 0° of incidence for an LET_{EFF} of 85MeV × cm^2/ mg .^{129}Xe ions at angle of 0° of incidence were used for an LET_{EFF} of 48 MeV × cm^2/ mg. Also,^{40}Ar ions at angle of 39.4° of incidence was used for an LET_{EFF} of 8MeV × cm^2/ mg, (see Table 5-1). For the SET testing, no external temperature force element was used during the characterization, the ambient temperature was set to 25°C.

Flux of approximately 10^4 ions/cm^2·s and fluence ≥ 1× 10^6 ions/cm^2 were used in each run. SETs were captured by monitoring.

Table 7-2. Summary of DP83561-SP SET Results Across MeV Levels

TEMP (°C)	ION	ANGLE OF INCIDENCE (°)	LET_{EFF} (MeV·cm^2/ mg)	FLUX (IONS/ CM^2·s)	FLUENCE (IONS/CM^2)	MAC - MDI CONFIGURATION	CURRENT (mA)				BEST CASE BER RATE	Link Loss X-SEC	PLL _X-SEC
							VDD1P1 (1.21)	VDD1P8 (1.89)	VDDA2P5 (2.62)	VDDIO (3.45)			
25	Au	0	85	1.00×10^2	1.00×10^6	RGMII - 1G	146.1	56.1	92.1	58	2.488E-08	4.99E-05	4.99E-05
25	Xe	0	48	1.00×10^2	1.00×10^6	RGMII - 1G	146	57	96.5	64	5.14487E-07	1.16E-05	1.16E-05
25	Ar	39.4	8	1.00×10^2	1.00×10^6	RGMII - 1G	146.4	55.8	91.8	58	2.846E-08	9.85E-06	9.85E-06

By monitoring extras signals on the scope cards, the different SET signatures were isolated and individual cross sections were created for each one. The trigger type and value used for each signal is described in Table 7-3.

Figure 7-5 through Figure 7-6 are plots of the SET cross sections vs. LET for the BER, link losses and PLL lock. Two sigma error bars, representing a confidence level of approximately 95% are plotted around each data point. A Weibull plot has been fitted to the data in Equation 1 (7) with the fit parameters listed in Table X-X. Events were seen at the lowest LET tested (8 MeV-cm2/mg) and 8 MeV-cm2/mg was used for the threshold LET. The cross sections at the highest LETeff tested (85 MeV-cm2/mg) were used for the limiting cross sections.

$$F(L) = A\left(1 - exp\left\{-\left[\frac{L-L_0}{W}\right]^S\right\}\right); L > L_0$$

where, ***F(L)*** is the event cross-section for a particular LET
A is the limiting cross-section
W is the width of the distribution
L_0 is the threshold LET
S is the shape parameter

Table 7-3. Weibull Fit Parameters

	Weibull Fit Paramenters			
	A	Lo	W	s
RGMII 1-G BER	2.20E-04	8	25	1.2
RGMII 1-G Link Loss	4.99E-05	8	25	0.9
RGMII 1-G PLL Lock	4.99E-05	8	25	0.9

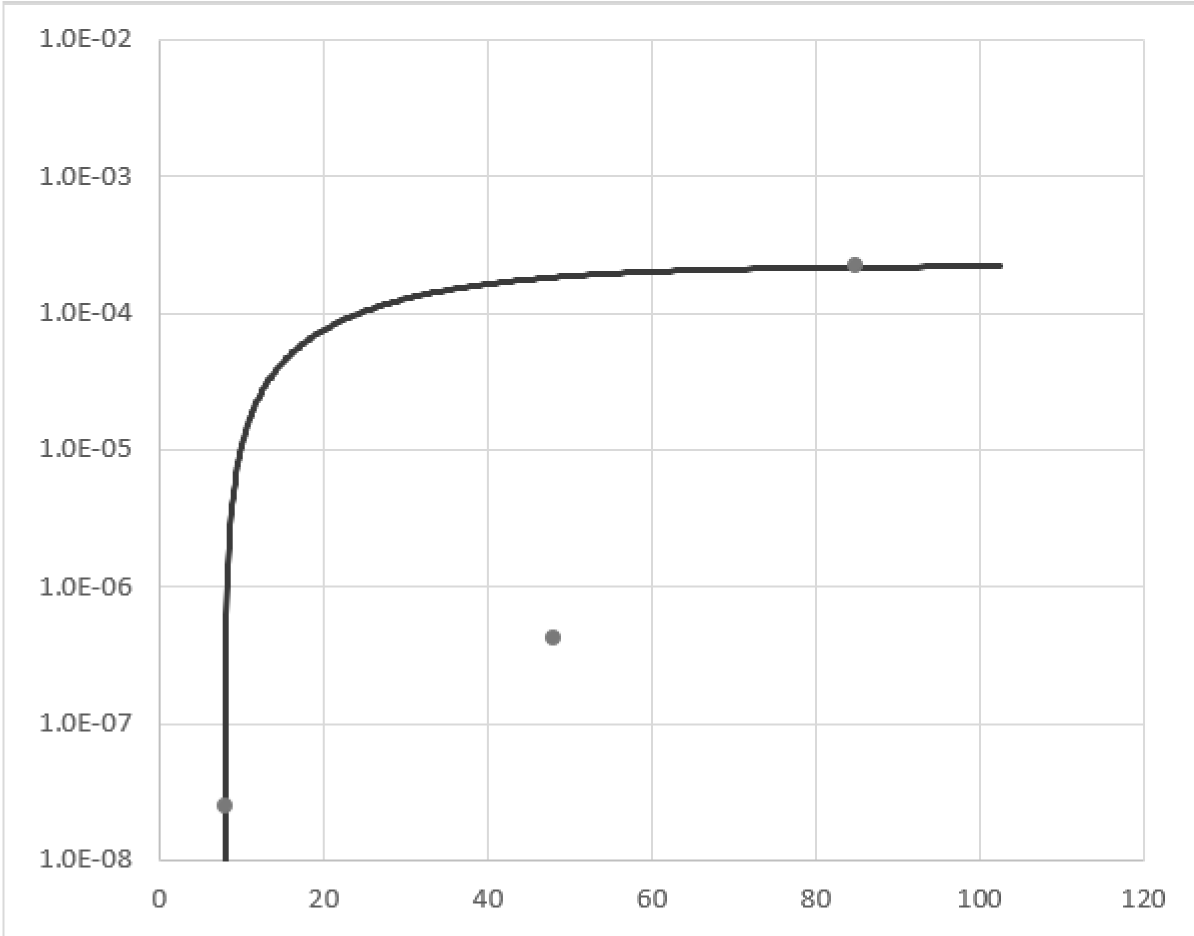


Figure 7-5. SET Cross Section vs. LETeff for BER in RGMII-1G Mode with a Weibull Plot Fitted to the Data

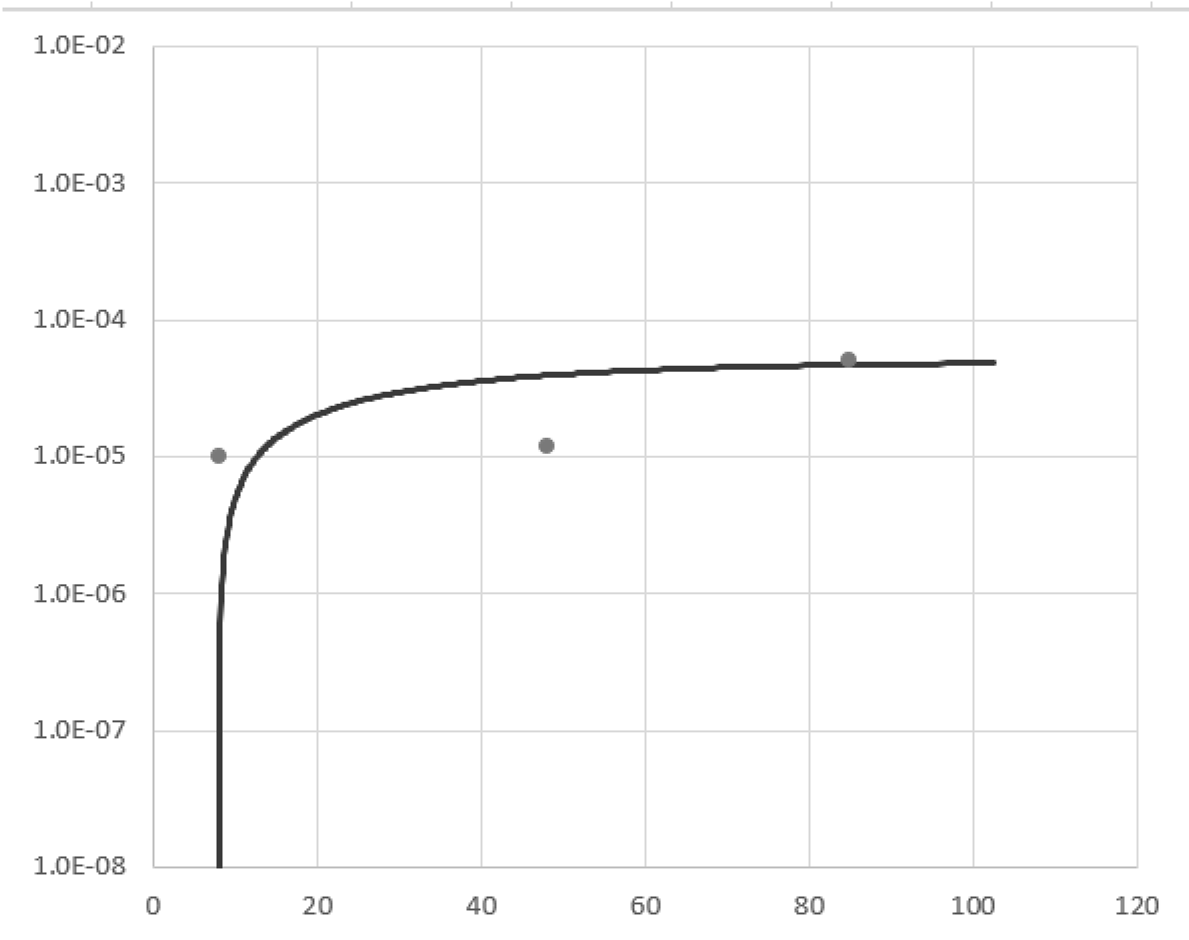


Figure 7-6. SET Cross Section vs. LETeff for Link in RGMII-1G Mode with a Weibull Plot Fitted to the Data

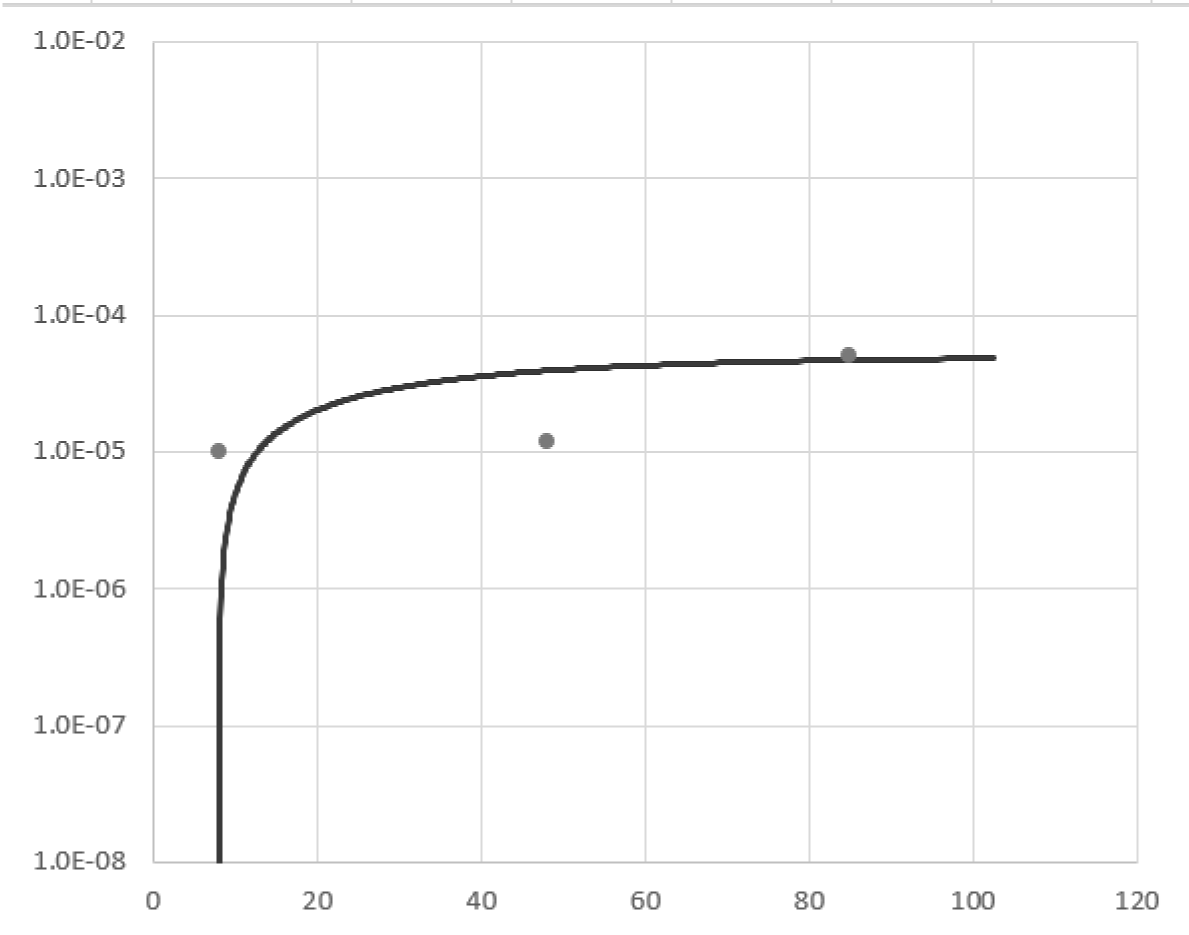


Figure 7-7. SET Cross Section vs. LETeff for PLL Lock in RGMII-1G Mode with a Weibull Plot Fitted to the Data

8 Summary

The purpose of this report is to summarize the DP83561-SP SEE performance under heavy-ions irradiation. The data shows the device is SEL free up to 121 MeV. Weibull fit was created when applicable and LEO (ISS) and GEO orbit rate calculations were calculated and presented. The worst case on orbit rate MTBE (mean-time between events) is shown to be on the order of 10^4 years.

A References

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12. D. Kececioglu, “Reliability and Life Testing Handbook”, Vol. 1, PTR Prentice Hall, New Jersey,1993, pp. 186-193.

10 Revision History

Changes from Revision * (May 2022) to Revision A (February 2025)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document	1
• Moved Single Event Transients (SET) to be a subset of Single Event Effects (SEE)	18

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