ISL70002SEH, ISL73002SEH

Single Event Effects (SEE) Testing of the ISL70002SEH and ISL73002SEH Synchronous Buck Regulators

Introduction

The high-energy proton and heavy ion environment encountered in space applications can cause a variety of single-event effects in electronic circuitry, including single event upset (SEU), single event transient (SET), single event functional Interrupt (SEFI), single event latch-up (SEL), single event burnout (SEB), and single event gate rupture (SEGR). These effects are divided into destructive and nondestructive SEE and can lead to system-level performance issues ranging from disruption to non-functionality and mission failure. This report summarizes the results of SEE testing performed on the ISL70002SEH synchronous buck regulator in 2011. The reported results for the base ISL70002SEH also apply to the ISL73002SEH variant. The parts are produced in the same assembly flow and are available in the same packages. They only differ in final assembly TID acceptance testing.

The most important result of this work can be simply expressed: In no instance did an SET or SEFI signature result in a visible increase of the converter output voltage, which is an important finding as the sensitive low voltage loads driven by a point-of-load regulator can be immediately destroyed by an overvoltage transient.

It should be noted that Renesas performs SEE testing as a routine part of the product development and validation sequence. In that context, a limited number of samples are tested at a limited number of linear energy transfer (LET) values. The generation of a rigorous cross section versus LET curve is a desirable objective but requires a large number of data points; limitations in available beam time and engineering and funding resources restricted the present work to a much more limited scope.

Product Description

The ISL70002SEH is a total dose and single-event effects hardened high efficiency monolithic synchronous buck regulator with integrated MOSFETs. This single chip power solution operates across an input voltage range of 3V to 5.5V and provides a tightly regulated output voltage that is externally adjustable from 0.8V to ~85% of the input voltage. Output load current capacity is 12A for $T_J \leq +150°C$. Two ISL70002SEH devices configured to current share can provide 19A total output current in what is effectively a 2-phase converter. The ISL70002SEH uses peak current-mode control with integrated error amp compensation and pin selectable slope compensation. The switching frequency is pin selectable to either 500kHz or 1MHz.

Up to 24A is possible from a single ISL70002SEH under certain conditions. See Addendum December 2017 for details on that testing.

The part features a comparator type enable input that can be used for simple digital on/off control or, alternately, can provide undervoltage lockout capability by precisely sensing the magnitude of an external supply voltage using an external voltage divider. A power-good signal indicates when the output voltage is within ±11% (typical) of the nominal output voltage. The regulator start-up is controlled by an analog soft-start circuit, which can be adjusted from approximately 2ms to 200ms using an external capacitor. ISL70002SEH fault protection features include input undervoltage, output undervoltage, and output overcurrent. Two devices can be synchronized to provide a complete power solution for large scale digital ICs such as field programmable gate arrays (FPGAs), most of which require separate core and I/O voltages.

The ISL70002SEH can operate two parts configured as a single 2-phase regulator resulting in nearly twice the load current capacity. In this mode, a redundant current sharing bus balances the load current between the two devices and communicates any fault conditions. In 2-phase operation, one part is designated the Master circuit and the other the Slave circuit. Master/Slave operation is controlled by the ISHSL pin; it is connected to DGND for Master operation and to DVDD for Slave operation, see Figure 2 for a detailed diagram of the 2-phase configuration. Also see the ISL70002SEH datasheet for diagrams and applications information. In 2-phase operation, the ISL70002SEH ICs run 180° out-of-phase to minimize the input ripple current, effectively operating as a single IC at twice the switching frequency. The Master error amplifier and compensation network control the overall 2-phase regulator. From a single-event effects testing viewpoint, Master and Slave operation are functionally different, requiring separate SET and SEFI testing for each of the two conditions.

The ISL70002SEH is hardened to achieve a total dose (TID) rating of 100krads(Si) at both high (50-300rad(Si)/s) and low (< 0.01rad(Si)/s) dose rates as specified in MIL-STD-883 test method 1019. High dose rate (HDR) hardness to the 100krad(Si) design level has been demonstrated and a low dose rate (LDR) test is currently at the 50krad(Si) downpoints with no failures. The ISL70002SEH is acceptance tested on a wafer-by-wafer basis at LDR to 50krad(Si) and at HDR to 100krad(Si).

The ISL73002SEH is physically identical to the ISL70002SEH. The ISL73002SEH is acceptance tested on a wafer-by-wafer basis at LDR to 50krad(Si), not at a high dose rate.

The ISL70002SEH is also SEE hardened to a linear energy transfer (LET) value of 86.4MeV•cm^2/mg. SEE hardening techniques used include device sizing, filtering and layout constraints. Single-event transients (SET) are a major issue in power management parts driving voltage-sensitive loads, and redundancy and majority voter techniques were used to harden the internal PWM control loop and provide superior performance in this environment. Additional SET hardening is achieved by specifying or restricting the values of certain external components.

Specifications for radiation hardened MILPRF-38535 QML devices are controlled by the Defense Logistics Agency (DLA) in Columbus, OH. The SMD is the controlling document.

Contents

1. SEE Testing

1.1 Test Objectives

The ISL70002SEH was tested to determine its susceptibility to destructive effects including single-event latch-up (SEL), single-event burnout (SEB), and single-event gate rupture (SEGR) and to nondestructive effects including single-event transient (SET) and single-event functional interrupt (SEFI). The results are discussed in that order. The sample sizes reflected the requirements of MIL-PRF-38535 (QML), and we used final version, production parts. A great deal of SEE testing was performed on earlier, prototype parts but this diagnostic work is not relevant to the final version and is hence not reported here.

1.2 Test Facility

Testing was performed at the Texas A&M University (TAMU) Cyclotron Institute heavy ion facility. This facility is coupled to a K500 super-conducting cyclotron, which is capable of generating a wide range of test particles with the various energy, flux, and fluence levels needed for advanced radiation testing.

1.3 Test Set-up

The majority of the SEE testing was carried out with the sample in an active configuration using either single or 2-phase operation. A schematic of the ISL70002SEH SEE test fixture for single part irradiation as used for the destructive SEE testing is shown in Figure 1. The test circuit is a single-phase synchronous buck DC/DC converter running at 500KHz or 1MHz and configured to accept an input voltage from 3V to 5.5V and generate a nominal 1.8V output voltage. The output current of the converter was set using a constant current electronic load. For the destructive SEE testing, the input voltage was used as the independent variable and was increased in 0.1V steps from a 6.2V starting value. The output voltage was set at 1.8V at an output current of 14A, which is 17% above the maximum rated current of 12A.

The part operates in a current sharing mode, in which two parts are configured as a 2-phase regulator resulting in nearly twice the load current capacity. The SET/SEFI testing was done in the 2-phase configuration, as the SEE responses of the part in the Master and Slave mode were expected to be different.

For the SET and SEFI testing, the ISL70002SEH samples were operated in a master-slave configuration forming a 2-phase converter. The switching frequency was 500KHz and the input voltage was either 3.0V or 5.5V. The output voltage was set at 1.0V at a total output current (both parts) of 12A, for an output current of 6A per part. The critical connections for 2-phase operation are listed below; see also the schematic in Figure 2.

- The LX pins of both parts are connected to separate inductors.
- PVIN, GND, SYNC, FB, ISHx, ISHREFx, and ISHCOM pins of the Master are connected directly to the corresponding pins of the Slave.
- The REF pins are connected through a 10Ω resistor.
- The M/S pin of the Master is connected to PVIN.
- The M/S pin of the Slave is connected to GND.
- The Master SS capacitor is twice the value of the Slave SS capacitor (0.22µF vs. 0.1µF).
- The ISHEN pins are connected to DVDD.
- The ISHSL pin of the Master is connected to GND.
- The ISHSL pin of the Slave is connected to DVDD.

Two test boards with a Master and Slave ISL70002SEH on each board were mounted to a test jig, which can be moved with respect to the ion beam to enable irradiation of either the Master or Slave sample. Using 20-foot coaxial cables, the test jig was connected to a switch box in the control room, which contained all of the monitoring equipment. The switch box allowed any one of the test circuits to be controlled and monitored remotely. Digital multimeters were used to monitor input voltage (V_{IN}), output voltage (V_{OUT}), and input current (I_{IN}). Four LeCroy

4-channel digital oscilloscopes were used to set the trigger levels and to monitor, capture, and store key signal waveforms.

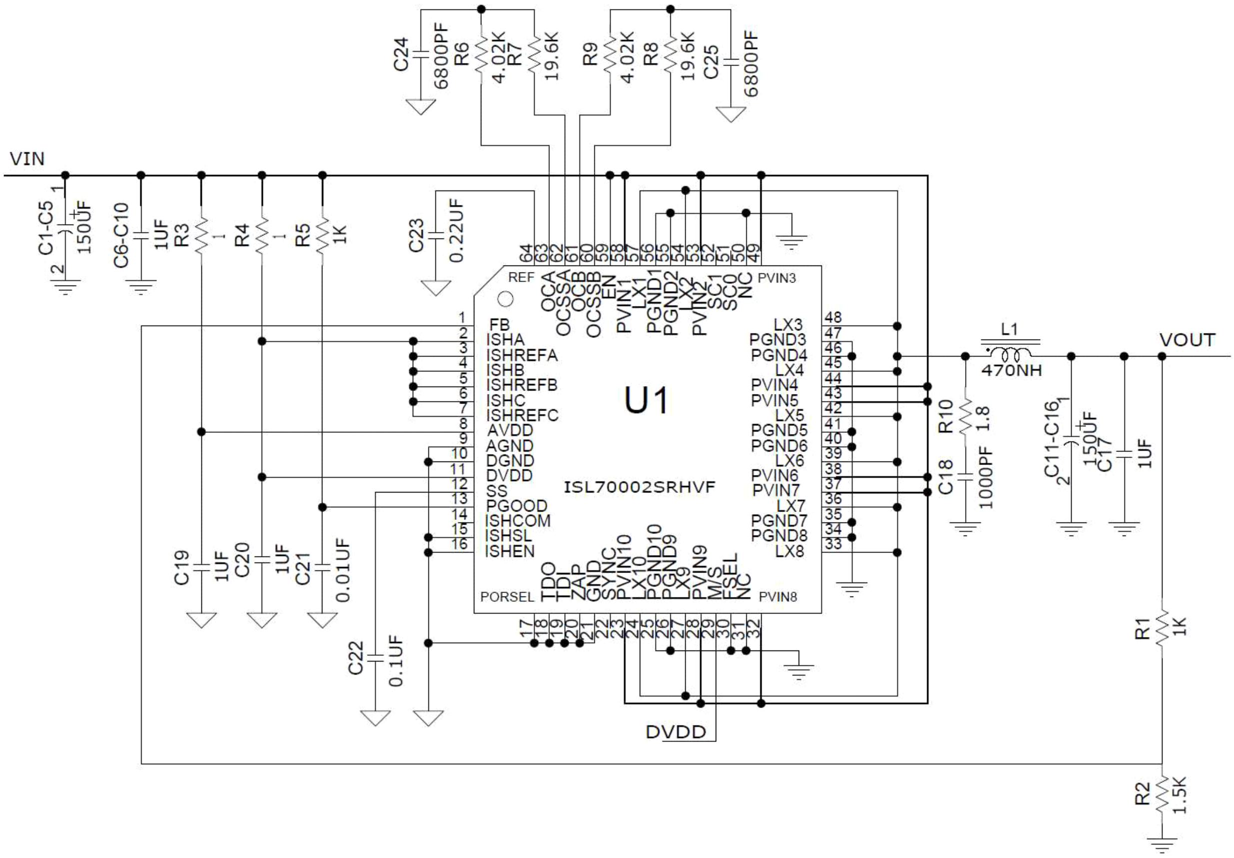

Figure 1. Schematic of the ISL70002SEH in the single operating mode, configured as a single-phase converter. [1]

1. This configuration was used for the destructive SEE testing.

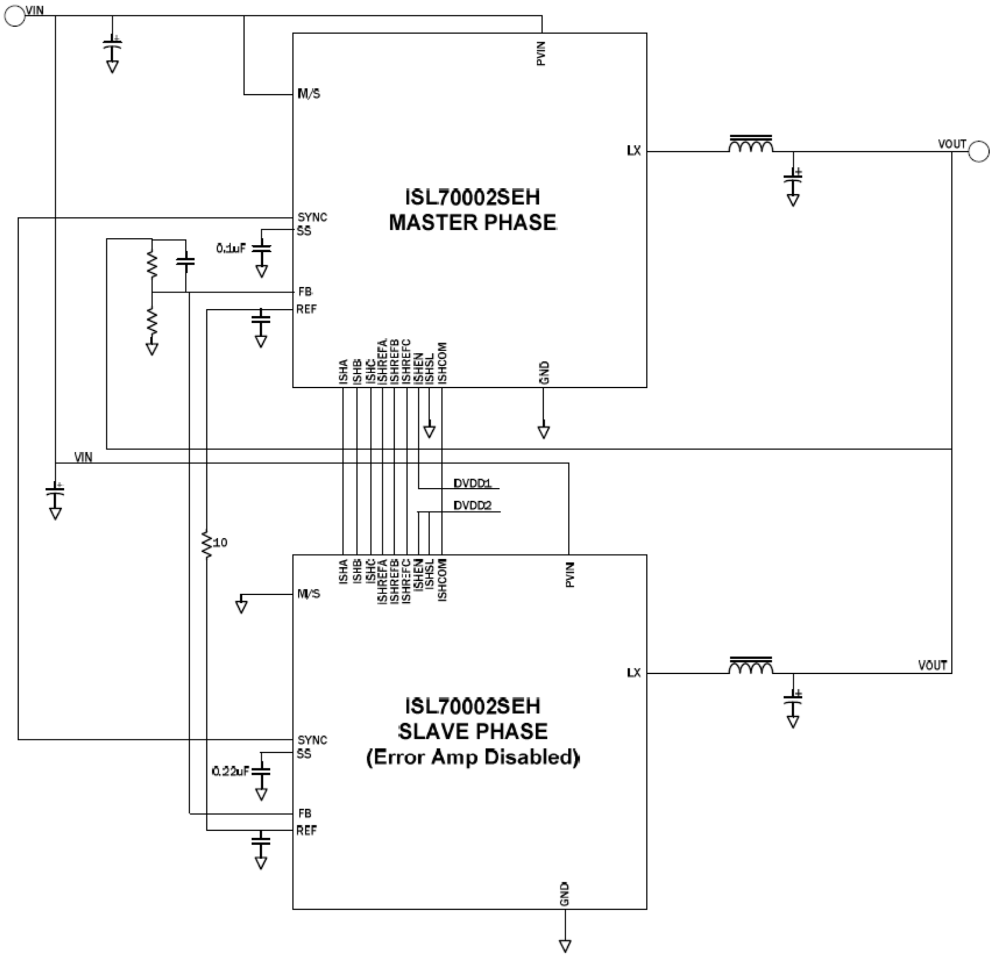

Figure 2. Schematic of the ISL70002SEH in the current share mode, configured as a 2-phase converter.[1]

1. This configuration was used for the SET and SEFI testing.

1.4 Destructive SEE Testing

For the SEL/SEB/SEGR tests, conditions were selected to maximize the electrical and thermal stresses on the device under test (DUT), therefore, ensuring worst-case conditions. The input voltage (V_{IN}) was used as the independent variable and was initially set to 6.2V, which is 0.5V above the absolute maximum rating of 5.7V and 0.7V above the recommended supply voltage of 5.5V for the device, and then increased in 0.1V or 0.2V increments. The output voltage (V_{OUT}) was set to 1.8V, while the output current (I_{OUT}) was set to 14A with the exception of four Slave mode irradiations in which the output current was 2A.

Case temperature was maintained at 125ºC by controlling the current flowing into a resistive heater bonded to the underside of the DUT. This ensured that the junction temperature of the DUT during irradiation exceeded the 125ºC maximum junction temperature anticipated for high reliability applications. The ISL70002SEH can be used with or without an external Schottky clamp diode, and destructive SEE testing was carried out in both configurations. For the destructive tests, all samples were irradiated with Au ions with the beam normal to the die surface, resulting in an LET of 86MeV•cm^2/mg. For these tests, the flux was 1×10^4ions/cm^2•sec and the fluence for each sample was 2×10^6ions/cm^2.

These were go-no-go tests and only the operating supply current was monitored as a destructive SEE indicator; SEE waveforms were not acquired. The failure criterion used for defining destructive SEE was a greater than 5% increase in operating input current (I_{IN}). I_{IN} is defined as the total current drawn by the device and is the sum of currents flowing into the PVINx (power), DVDD (digital), and AVDD (analog) supply pins. Measuring at zero load current is thus equivalent to measuring the sum of the analog and digital quiescent supply currents, which are a good indicator of part functionality. Failed devices were not further irradiated.

Table 1 summarizes the results of the destructive SEE tests, while Figure 3 summarizes the results in bar chart format. The chart shows sample size and pass/fail results for each of the input voltage levels used as well as the total fluence for each level. The aggregate fluence at an input voltage of 6.2V was $12×(2×10^6) = 2.4×10^7$ions/cm^2. Because no failures were encountered, the destructive SEE cross section was estimated by the well known relationship cross section = 1/fluence, resulting in an estimated cross section of $4.16×10^{-8}$cm^2 at the maximum input voltage of 6.2V. We conclude that the part is free of destructive SEE up to a conservative maximum input voltage of 6.2V under worst-case conditions, in either the Schottky or non-Schottky configuration.

Table 1. Results of destructive SEE testing of ISL70002SEH samples under various conditions.[1]

Samples Tested	V_{IN}	I_{OUT}	Conditions	Pass	Fail
4	6.2V	14A	Master with external Schottky diode	4	0
4	6.2V	14A	Master without external Schottky diode	4	0
2	6.2V	2A	Slave with external Schottky diode	2	0
2	6.2V	Zero	Master, disabled	2	0
1	6.3V	14A	Master with external Schottky diode	1	0
4	6.4V	14A	Master with external Schottky diode	3	1
2	6.4V	14A	Master without external Schottky diode	2	0
2	6.4V	2A	Slave with external Schottky diode	2	0
2	6.4V	Zero	Master, disabled	2	0
1	6.5V	14A	Master with external Schottky diode	1	0
1	6.6V	14A	Master with external Schottky diode	0	1
3	6.6V	14A	Master without external Schottky diode	0	2

1. All irradiations were performed at zero degree incident beam angle using Au ions at an LET of 84MeV•cm^2/mg. The flux and fluence for each run were $1×10^4$ions/cm^2•s and $2×10^6$ions/cm^2, respectively. The input voltage was used as the independent variable and ranged from 6.2V to 6.6V. The Master destructive SEE testing was performed with no Slave device present. These results are further summarized in graphical format in Figure 3.

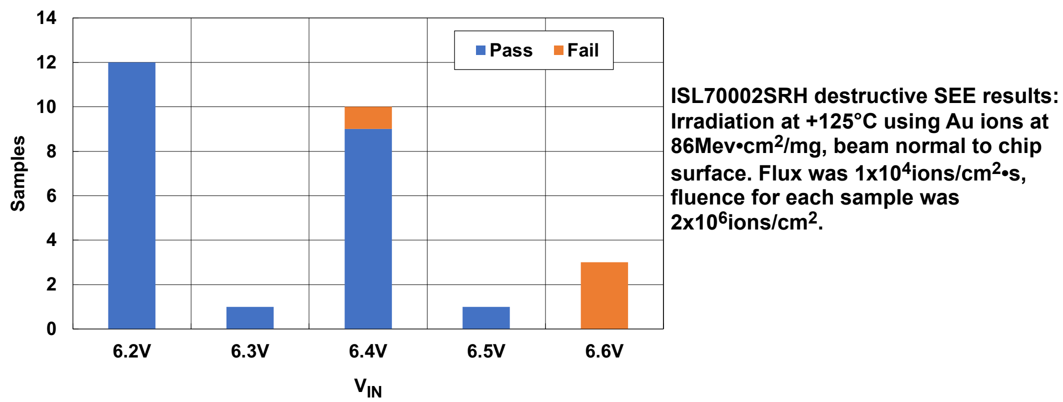

Figure 3. Summary of ISL70002SEH destructive SEE test results. [1]

1. Samples were tested with increasing input voltage (V_{IN}, plotted on the horizontal axis) until failure, see text. The chart shows sample size and pass/fail results for each of the input voltage levels used. The fluence per sample for each run was $2×10^6$ions/cm^2, and the aggregate fluence at 6.2V was $2.4×10^7$ions/cm^2. The destructive SEE cross section at an input voltage of 6.2V can be estimated as 1/fluence, which equals $4.16×10^{-8}$cm^2.

2. SET Testing

Single-event transient (SET) testing of the ISL70002SEH was carried out using eight samples of the production part. The samples were configured as a 2-phase converter operated at 1.0V output voltage and 12A (6A per part) output current, using input voltages of 3.0V and 5.5V, which represent the minimum and maximum input voltages, respectively. A Master or a Slave sample was irradiated in each run, with the other part of the 2-phase converter located outside the beam. Low LET irradiations were performed at zero degree incident beam angle using Ag ions at an LET of 43MeV•cm^2/mg. High LET irradiation was carried out at 60 degree incident beam angle using Ag ions and at zero degree incident beam angle using Au ions; both conditions result in an effective LET of 86MeV•cm^2/mg. This approach was used to evaluate the effects of beam angle at constant LET. The flux for each run was 5×10^{4}ions/cm^2•s.

Table 2 and Table 3 summarize the results of the SET testing for the Master and Slave configurations, respectively. In no instance did an SET or SEFI signature result in a visible increase of the converter output voltage.

Table 2. SET testing for Master irradiation at 3.0V and 5.5V input voltage, defining SET as a Master LX pulse width perturbation in excess of a ±500ns threshold for the 3.0V tests and a ±300ns threshold for the 5.5V tests.[1]

V_{IN} (V)	Mode	LET (MeV•cm^2/mg)	Species (Ion and angle)	Fluence (*ions*/cm^2)	SET Events, Master LX	Cross section, Master LX (cm^2)	Events, Slave LX
3.0	Master	86	Au at 0°	4×10^6	679	1.70 x 10^{-4}	1350
5.5	Master	86	Au at 0°	4×10^6	469	1.17 x 10^{-4}	1060

1. The samples were configured as a 2-phase converter operated at 1.0V output voltage and 12A output current. The irradiations were carried out at an effective LET of 86MeV•cm^2/mg. The flux for each run was 5×10^{4}ions/cm^2•s. The LET is expressed in MeV•cm^2/mg, fluences in ions/cm^2, and cross sections in cm^2. The reported Slave LX events are a response of the Slave attempting to correct the undervoltage condition caused by the Master SET, so they do not constitute SET events as they are not directly caused by ion strikes. The Slave is outside the beam so there are no fluence and cross section numbers associated with the Slave event counts, which are shown for information only.

Table 3. SET testing for Slave operation at 3.0V and 5.5V input voltage, again using a pulse width perturbation window of ±500ns for the 3.0V tests and a window of ±300ns for the 5.5V tests.[1]

V_{IN} (V)	Mode	LET (MeV•cm^2/mg)	Species (Ion and angle)	Fluence (ions/cm^2)	SET Events, Slave LX	Cross section, Slave LX (cm^2)	Events, Master LX
3.0	Slave	86	Ag at 60°	7×10^6	766	1.09 x 10^{-4}	
		86	Au at 0°	4×10^6	457	1.14 x 10^{-4}	194
		43	Ag at 0°	1×10^7	1257	1.26 x 10^{-4}	
5.5	Slave	86	Ag at 60°	1.35×10^7	103	7.63 x 10^{-6}	
		86	Au at 0°	4×10^6	409	1.02 x 10^{-4}	111
		43	Ag at 0°	7.5×10^6	744	9.92 x 10^{-5}	

1. The samples were configured as a 2-phase converter operated at 1.0V output voltage and 12A output current, using input voltages of 3.0V and 5.5V with the Slave part irradiated as shown in the Mode column. The low LET irradiations were performed at zero degrees (defined as normal to the chip surface) incident beam angle using Ag ions at an LET of 43MeV•cm^2/mg. The high LET irradiations were carried out at 60 degree incident beam angle using Ag ions and at zero degree incident beam angle using Au ions; both conditions result in an effective LET of 86MeV•cm^2/mg. The flux for each run was 5×10^{4}ions/cm^2•s, and the aggregate fluences are shown in the table. LET is expressed in MeV•cm^2/mg, fluences in ions/cm^2 and cross sections in cm^2. As in Table 2, the reported Master LX events are a response of the Master attempting to correct the undervoltage condition caused by the Slave SET, so they do not constitute SET events as they are not directly caused by ion strikes. The Master LX events are shown for the Au at 0o (LET = 86MeV•cm^2/mg) case only. The Master is outside the beam so there are no fluence and cross section numbers associated with the Master event counts, which are shown for information only.

SET was defined as an LX pulse widening or narrowing exceeding 500ns for the 3.0V tests and exceeding 300ns for the 5.5V tests. Master SET monitoring was carried out with the zero degree Au beam only, while Slave SET was investigated for both low and high LET, with a high LET split between Ag at 60° and Au at 0°, both of which equate to an LET of 86MeV•cm^2/mg. The results for the 0° vs. 60° beam split at 86MeV•cm^2/mg were somewhat inconclusive; in most cases the 60° SET count was approximately twice that of the normal beam count, with the exception of the 5.5V Slave runs. Table 2 and Table 3 show the aggregate fluences and the calculated SET cross sections for each test condition.

It should be carefully noted that the Slave LX perturbations reported in Table 2 and the Master LX perturbations in Table 3 represent a response by the non-irradiated (out of beam) part to SET events in the irradiated part. In this sequence, the non-irradiated part attempts to correct the undervoltage condition caused by the SET in the irradiated part. We do not consider these responses by the non-irradiated parts to constitute SET events, as they are not directly caused by ion strikes. The non-irradiated part is outside the beam so there are no fluence and cross section numbers associated with its event counts. We do note that the event counts for the non-irradiated part are about twice that of the irradiated part for the Master irradiation case, while the Slave irradiation data shows about half the event counts for the non-irradiated part.

Figure 4 through Figure 11 show representative SET waveforms for input voltages of 3.0V and 5.5V and for Master and Slave operation. The single-event functional interrupt (SEFI) data shown in SEFI Testing, is a subset of the SET data but are discussed separately as different phenomena are involved. The perturbation of the converter output voltage during SET events did not exceed -1% at any time and no increases were observed, indicating effective operation of the redundant sections of the part.

Figure 4 and Figure 5 show SET signatures with the part operated at 3.0V input, with the Master irradiated. The Figure 4 Master trace shows one narrowed LX pulse followed by a wide Slave pulse and recovery of the converter. In Figure 5, both the Master and Slave traces show one narrowed LX pulse followed by a wide pulse and recovery of the converter. The output voltage perturbation (red trace) for both sets of signatures was less than -1%.

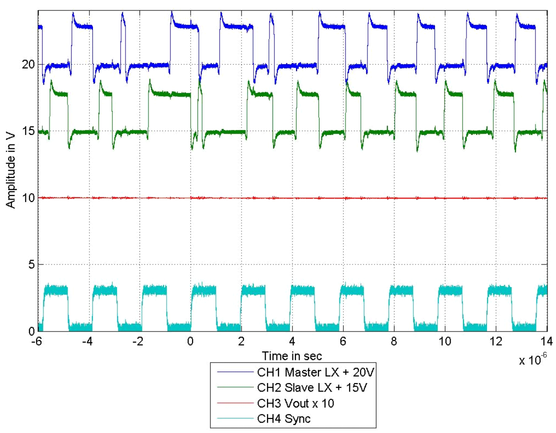

Figure 4. ISL70002SEH SET signature at LET = 86MeV•cm^2/mg, flux 1×10^{4}ions/cm^2•s. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The two upper traces show the Master (blue) and Slave (green) LX output waveforms. The lower trace (aqua) is the SYNC waveform, and the red trace is the key parameter: the output voltage of the converter, multiplied by a 10X scale factor. The Master trace shows one narrowed LX pulse, a wide Slave pulse and recovery of the converter. The output voltage perturbation (red trace) is less than -1%. The horizontal axis is calibrated at 2 microseconds per division.

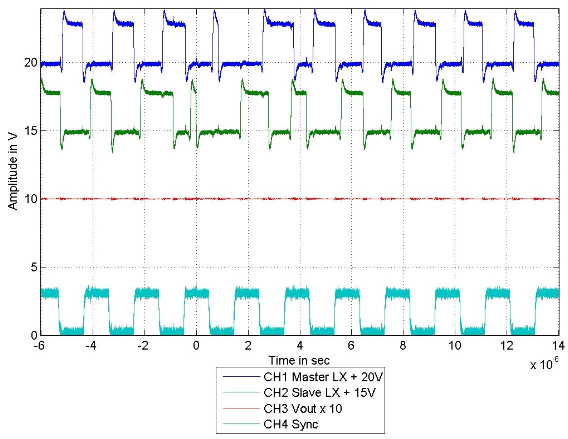

Figure 5. ISL70002SEH SET signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The trace colors and scale factors are as in Figure 4. Both the Master and Slave traces show one narrowed LX pulse followed by a wide pulse and recovery of the converter. The output voltage perturbation (red trace) is less than -1%.

Figure 6 and Figure 7 show SET signatures with the part operated at 3.0V input, with the Slave irradiated. The Figure 6 Master and Slave traces show one narrowed LX pulse followed by a wide pulse and subsequent recovery of the converter. In Figure 7, the Slave trace shows one wide LX pulse followed by two narrow pulses and recovery of the converter. The output voltage perturbation (red trace) was less than -1%.

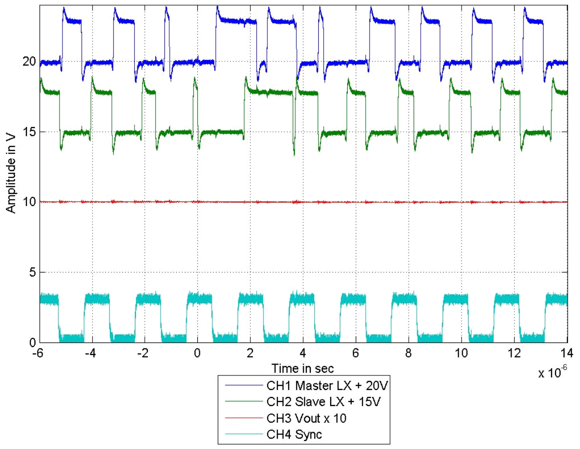

Figure 6. ISL70002SEH SET signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Slave irradiated. The trace colors and scale factors are as in Figure 4. The Master and Slave traces show one narrow LX pulse followed by a wide pulse and recovery of the converter. Output voltage change is less than -1%.

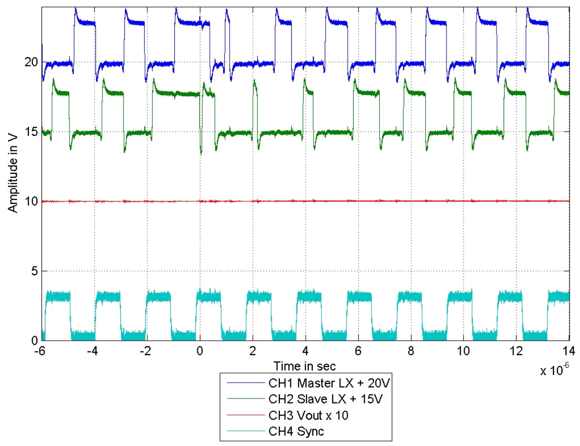

Figure 7. ISL70002SEH SET signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Slave irradiated. The trace colors and scale factors are as in Figure 4. The Slave trace shows one wide LX pulse followed by narrow pulses and recovery of the converter. The output voltage change is less than -1%.

Figure 8 and Figure 9 show representative SET signatures with the part operated in a current sharing configuration at 5.5V input, with the Master irradiated. The two upper traces (blue and green) show the Master and Slave LX (output) waveforms, which are offset by 20V and 15V from the origin for clarity. The lower trace (aqua) is the SYNC waveform, and the red trace is the output voltage of the converter multiplied by a factor of ten. The Figure 8 Master trace shows one lengthened LX pulse followed by perturbation of the Slave pulse train and by recovery of the converter through several narrow pulses. The Figure 9 Master trace shows one narrow LX pulse followed by a wide Slave pulse and recovery of the converter. The output voltage perturbation (red trace) for both sets of signatures was less than -1%.

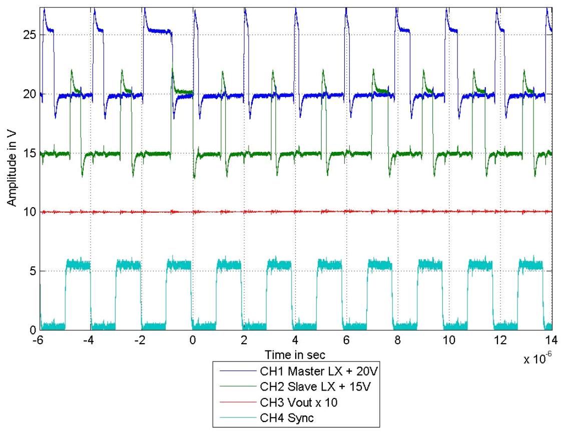

Figure 8. ISL70002SEH SET signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 5.5V input, with the Master irradiated. The trace colors and scale factors are as in Figure 4. The Master trace shows one lengthened LX pulse; this is followed by perturbation of the Slave and by recovery of the converter through several narrow pulses. The output voltage change is less than -1%.

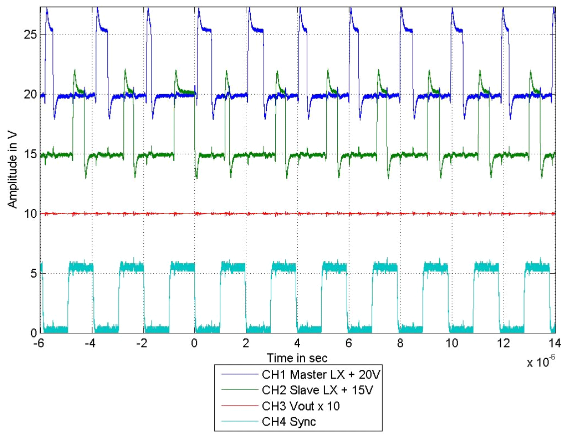

Figure 9. ISL70002SEH SET signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 5.5V input, with the Master irradiated. The trace colors and scale factors are as in Figure 4. The Master trace shows one narrowed LX pulse; this is followed by a wide Slave pulse and recovery of the converter. Output voltage change is less than -1%.

Figure 10 and Figure 11 show SET signatures with the part again operated in a current sharing configuration at 5.5V input, but this time with the Slave irradiated. The two upper traces (blue and green) show the Master and Slave LX (output) waveforms. The lower trace (aqua) is the SYNC waveform, and the red trace is the output voltage of the converter, again multiplied by a factor of 10. The Figure 10 Slave trace shows one slightly narrowed LX pulse followed by wide Master and Slave pulses and subsequent recovery of the converter. The Figure 11 Master trace shows one widened LX pulse followed by a wide Slave pulse and recovery of the converter by four narrow pulses. The output voltage perturbation (red trace) for both sets of signatures was less than -1%.

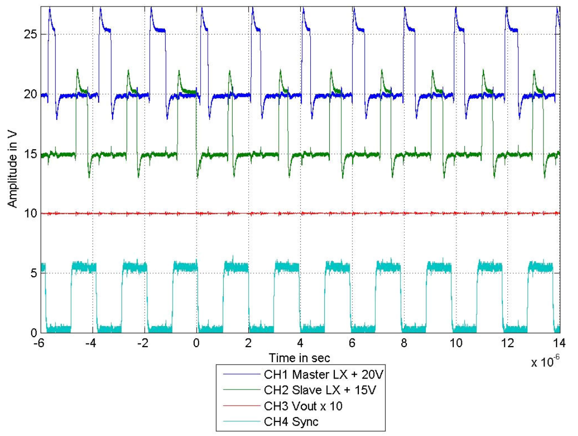

Figure 10. ISL70002SEH SET signature at LET = 86MeV•cm²/mg. The part is operated as a 2-phase converter at 5.5V input, with the Slave irradiated. The trace colors and scale factors are as in Figure 4. The Slave trace shows one slightly narrowed LX pulse followed by wide Master and Slave pulses and recovery of the converter. The output voltage change is less than -1%.

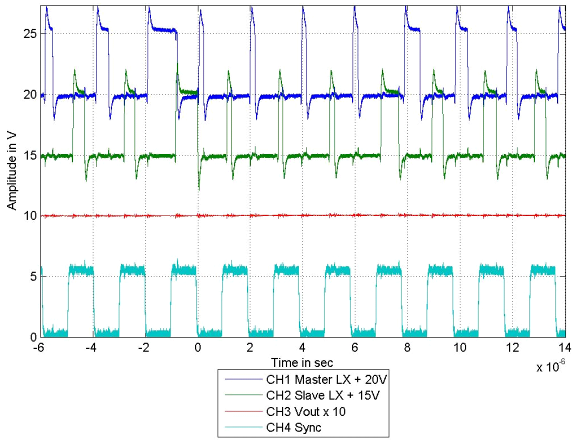

Figure 11. ISL70002SEH SET signature at LET = 86MeV•cm²/mg. The part is operated as a 2-phase converter at 5.5V input, with the Slave irradiated. The trace colors and scale factors are as in Figure 4. The Master trace shows one widened LX pulse followed by a wide Slave pulse and recovery of the converter by four narrow pulses. The output voltage change is less than -1%.

3. SEFI Testing

Single-event functional interrupt (SEFI) phenomena at low input voltage were encountered in earlier ISL70001SRH testing[1] and were therefore considered a key aspect of the present work. SEFI phenomena for the ISL70001SRH were encountered only at low input voltage (3.0V) and at high LET (84MeV•cm²/mg), and the same result was encountered in the present work. None of the SEFI events observed resulted in an increase of the converter output voltage.

A brief discussion of the formal definition of SEFI is in order. For the purposes of this report, a single-event functional interrupt is defined as a soft error: a disruption of the normal operation of the part, followed by either an assisted (for example through a reset or a system power-down/power-up followed by a soft-start cycle) recovery or a non-assisted recovery through a normal soft-start cycle. It is our position that SEFI is by definition a nondestructive effect; some researchers in the field have recently defined SEFI as applying to destructive effects as well, but the writer disagrees with this interpretation. A destructive SEFI is not an interrupt but a destructive failure, and if such a phenomenon is reported it needs to be a new SEE category or be included in existing SEE categories such as SEGR, SEL, and SEB.

Table 4 shows a summary of the SEFI results, which represent a subset of the SET results. Parts were irradiated in the Master and Slave configurations, with input voltages of 3.0V and 5.5V, output voltage of 1.0V and output current of 12A (6A per part). The species used were Au and Ag at an LET of 86MeV•cm²/mg and 43MeV•cm²/mg, respectively.

1. N. W. van Vonno, L. W. Pearce, H. W. Satterfield, E. T. Thomson, A. P. Williams, T. E. Fobes, P. J. Chesley and J. S. Gill, ‘Total Dose and Single Event Testing of a Hardened Point of Load Regulator’, 2010 *IEEE Radiation Effects Data Workshop Record*.

Table 4. Results of Single-Event Functional Interrupt Testing of ISL70002SEH Samples at 3.0V and 5.5V Input Voltage for Master and Slave Operation. [1]

Mode	V_{IN} (V)	V_{OUT} (V)	I_{OUT}, per part (A)	Ion	LET (MeV•cm²/mg)	Samples	Total fluence (ions/cm²)	Total SEFI Events	Cross Section (cm²)
Master	3.0	1.0	6	Au	86	4	4.4×10^{7}	42	9.50×10^{-7}
Master	3.0	1.0	6	Ag	43	4	4.4×10^{7}	0	2.26×10^{-8}
Slave	3.0	1.0	6	Au	86	5	5.5×10^{7}	26	4.70×10^{-7}
Slave	3.0	1.0	6	Ag	43	4	4.4×10^{7}	0	2.26×10^{-8}
Master	5.5	1.0	6	Au	86	4	4.4×10^{7}	0	2.26×10^{-8}
Master	5.5	1.0	6	Ag	43	3	3.3×10^{7}	0	4.70×10^{-7}
Slave	5.5	1.0	6	Au	86	4	4.4×10^{7}	0	2.26×10^{-8}
Slave	5.5	1.0	6	Ag	43	3	3.3×10^{7}	0	4.70×10^{-7}

1. All irradiations were performed at 0° incident beam angle. If no SEFI was observed, the cross section was again calculated as 1/fluence.

SEFI events were observed at 3.0V input and LET of 86MeV•cm²/mg only, with the event count in the Slave mode approximately half that of that for the Master configuration count. For 3.0V operation at a lower LET of 43MeV•cm²/mg and for 5.5V operation at both LET values, no SEFI events were encountered. If no SEFI was observed, we calculated the cross sections as 1/fluence. All SEFI signatures observed showed a non-assisted recovery to normal operation. Some were restarts, while others were a hiccup cycle (a dummy soft-start cycle) followed by a restart. The recovery time is a function of the value of the soft-start capacitor on the evaluation board used as an SEE fixture. The SEFI cross sections ranged from 2.26×10^{-8} to 9.50×10^{-7}cm², indicating a low probability of occurrence of this phenomenon.

Figure 12 through Figure 18 show SEFI signatures with the part operated as a 2-phase converter at 3.0V input, with the Master or Slave irradiated. The SEFI signatures are somewhat similar; following disruption of the LX signals, the LX outputs tri-state, the current through the inductor decays to zero, at which time the LX output rises to V_{OUT} and the part initiates a soft-start (SS) sequence to recover. We have plotted these phenomena on both the microsecond and millisecond scales. The output voltage (the red trace in the microsecond scale plots and the aqua trace in the millisecond plots) drops to zero while the soft-start cycle progresses; again, in no case did we observe a SEFI resulting in an output voltage increase.

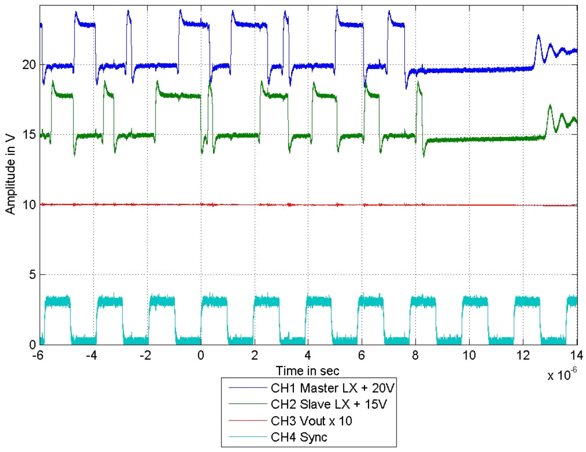

Figure 12. ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The trace colors and scale factors are as in Figure 4. Both LX outputs tri-state, the current through the inductor decays to zero, the LX output rises to V_{OUT} and the part initiates a soft-start (SS) sequence; see the compressed time scale plots in Figure 14 and Figure 15 as examples.

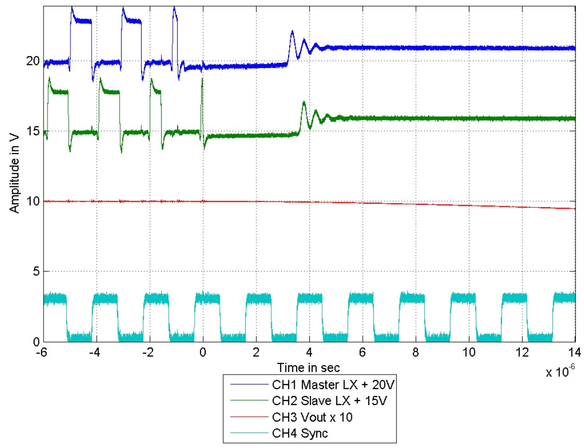

Figure 13. ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The trace colors and scale factors are as in Figure 4. Both LX outputs tri-state, the current through the inductor decays to zero, the LX output rises to V_{OUT} and the part initiates a soft-start (SS) sequence; see the compressed time scale plots in Figure 14 and Figure 15 as examples.

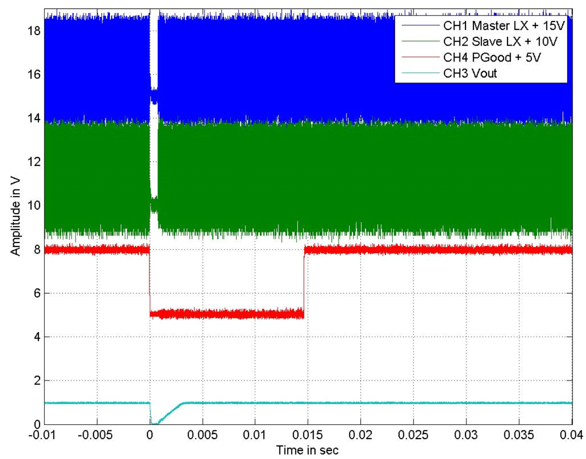

Figure 14. Compressed scale ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The two upper traces show the Master (blue) and Slave (green) LX output waveforms. The lower trace (aqua) is the output voltage of the converter, and the red trace is the PGOOD output signal (offset by 5V). Both LX outputs tri-state. In ~1ms the ISL70002SEH initiates a normal soft start without external intervention. Note: The horizontal axis is calibrated at 5ms per division.

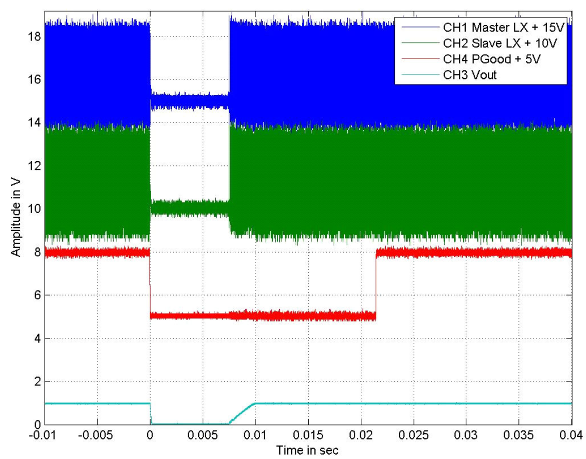

Figure 15. Compressed scale ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The two upper traces show the Master (blue) and Slave (green) LX output waveforms. The lower trace (aqua) is the output voltage of the converter, and the red trace is the PGOOD output signal. Both LX outputs tri-state, the ISL70002SEH goes through a hiccup cycle (dummy soft-start cycle) followed by a normal soft-start without external intervention. Note: The horizontal axis is calibrated at 5ms per division.

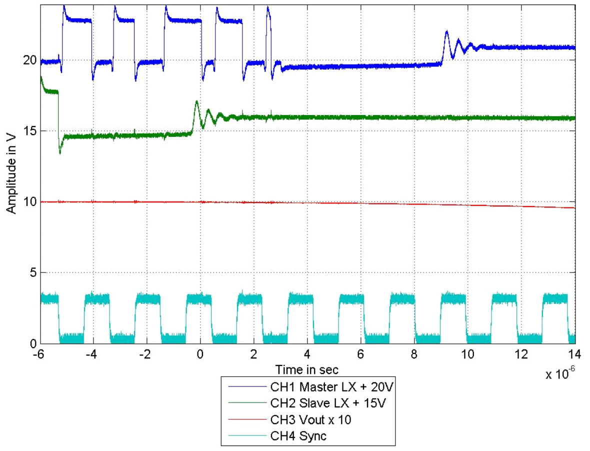

Figure 16. ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Slave irradiated. The trace colors and scale factors are as in Figure 4. The Slave tri-states and alerts the Master which also tri-states. As each LX output tri-states, the current through each inductor decays to zero, the LX output rises to V_{OUT} and the part initiates a soft-start (SS) sequence; see the compressed time scale plot in Figure 18.

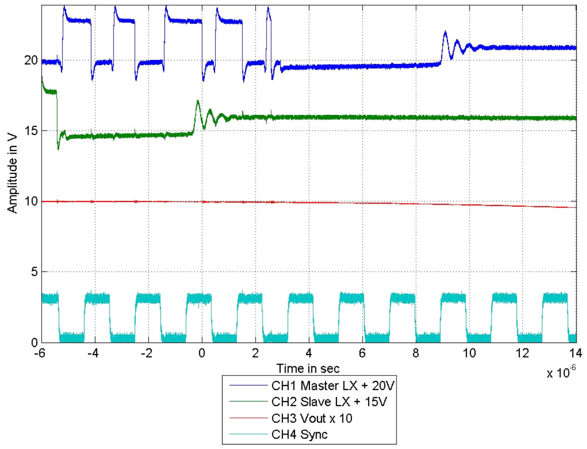

Figure 17. ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Slave irradiated. The trace colors and scale factors are as in Figure 4. Both LX outputs tri-state, the current through the inductor decays to zero, the LX output rises to V_{OUT} and the part initiates a soft-start (SS) sequence; see the compressed time scale plot in Figure 18 as an example.

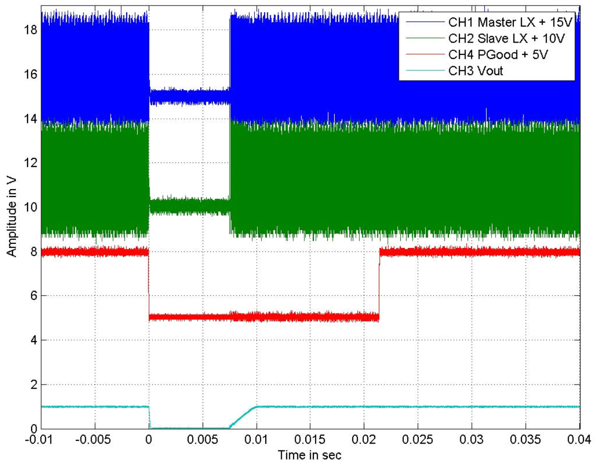

Figure 18. Compressed scale ISL70002SEH SEFI signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Slave irradiated. The two upper traces show the Master (blue) and Slave (green) LX output waveforms. The lower trace (aqua) is the output voltage of the converter, and the red trace is the PGOOD output signal. Both LX outputs tri-state, and the part goes through a hiccup cycle followed by a normal soft-start without external intervention. Note: The horizontal axis is calibrated at 5ms per division.

4. Clock Phase Shift Observations

During operation at 500kHz in the 2-phase configuration, when irradiating the Master at V_{IN} = 3.0V and LET of 86MeV•cm^2/mg, we observed few clock (and LX) phase shift SET events of less than 1µs duration. A total of 12 occurrences of this event were noted. As in the SEFI events, these were not observed at V_{IN} = 3.0V and LET of 43MeV•cm^2/mg, or with V_{IN} = 5.5V at any LET. There was negligible V_{OUT} movement similar to the LX pulse width captures. For a total of 12 occurrences and a total fluence of 4.4×10^7 the cross section of the clock phase shift phenomenon may be estimated as 2.73×10^{-7} cm^2. Figure 19 shows a sample clock phase shift SET signature. As expected, the clock phase shift causes an immediate LX phase shift. However, the peak current control architecture of the part terminates the shifted LX pulse early because of the increased inductor current, resulting in no observable V_{OUT} movement.

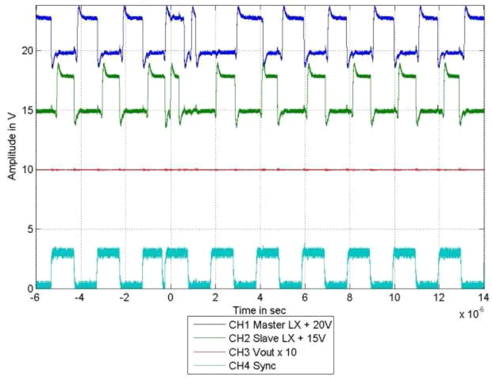

Figure 19. ISL70002SEH clock phase shift signature at LET = 86MeV•cm^2/mg. The part is operated as a 2-phase converter at 3.0V input, with the Master irradiated. The two upper traces show the Master (blue) and Slave (green) LX output waveforms. The lower trace (aqua) is the SYNC (clock) waveform, and the red trace is the output voltage of the converter multiplied by a 10X scale factor. The SYNC signal upsets resulting in an immediate LX phase shift, but the overcurrent sensor function detects the increase in inductor current and terminates the shifted LX pulse. The horizontal axis is calibrated at 2µs per division.

5. Conclusions

The ISL70002SEH SEE test results clearly demonstrate the effectivity of the hardened by design approach used for the part. SEL/SEB/SEGR immunity was demonstrated to a maximum input voltage of 6.2V at an effective LET of 86MeV•cm^2/mg under worst-case conditions, including an output current of 14A and a case temperature of 125ºC.

The SET results indicate the part architecture is highly effective in limiting SETs to less than one LX pulse perturbation and less than -1% perturbation of the output voltage to an effective LET of 86MeV•cm^2/mg, with the part operating at 14A output current at 1.0V output voltage. In all SET testing, the parts were configured in a current sharing mode, with a Master and Slave part configured as a 2-phase converter. In no instance did the SET (or for that matter the SEFI or clock phase shift signatures) result in a visible increase of the converter output voltage, which is an important result as the sensitive low voltage loads driven by these point-of-load regulators can be immediately destroyed by an overvoltage transient.

A limited number of single-event functional interrupts (SEFI) were encountered as a subset of the single-event transient (SET) testing. SEFI was observed only at an effective LET of 86MeV•cm^2/mg and at an input voltage of 3.0V, with no SEFI signatures observed at 3.0V and an LET of 43MeV•cm^2/mg or at 5.5V input voltage for either LET value. The observed event count in the Slave mode was approximately half that of that for the Master configuration, which is consistent with the reduced functionality of the Slave device in this mode. In all SEFI signatures the device recovered to normal operation without external intervention, and the estimated cross-sections of the SEFIs were shown to be quite small, with values ranging from 2.26×10^{-8} to $9.50\times10^{-7}cm^2$, indicating a low probability of occurrence.

Finally, we observed few clock (and LX) phase shift SET events of less than 1µs. These were observed while irradiating the Master at V_{IN} = 3.0V and LET of 86MeV•cm²/mg only. There was negligible V_{OUT} movement, similar to the SET captures. For a total of 12 occurrences and a total fluence of 4.4×10^7 the cross section of the clock phase shift phenomenon can be estimated as $2.73\times10^{-7}cm^2$.

6. Addendum December 2017

Considerable interest in operating the ISL70002SEH at currents above the originally prescribed limits has motivated investigation into higher current ratings. This addendum describes the testing done to study destructive SEE phenomenon at these higher currents.

The originally prescribed limit of 12A was based on electromigration considerations for when the part was operated at a junction temperature of 150°C. Subsequently, a limit of 14A was stipulated if the junction temperature was maintained below 125°C. Purely electromigration considerations allow current up to 24A, but the original SEE investigation only tested for destructive SEE at currents to 14A. Consequently, the 14A limitation was adopted in deference to the SEE testing. To allow higher currents, testing under ion beam irradiation needed to be done at those higher currents. It is this higher current SEE testing that is described here. The testing described here was done at the TAMU Cyclotron Institute on December 3, 2017.

The first step was to operate parts at higher currents without ion beam. Inventory parts of ISL70002SEHVFE (with heatsink) were mounted with the heatsink soldered down to the board on the dual part SEE evaluation boards. Parts were tested to above 48A for a dual and to above 24A for a single. The parts were operated at 25°C ambient. It was found that parts proceeded into thermal runaway when operated as a single unit above 18A without a Schottky diode (ON Semiconductor MBRS340T3G) from GND to LX (the switching node). See TB515 for more details about the electrical testing. Consequently, radiation testing focused on single units operating at 18A without a Schottky and 24A with a Schottky.

While being SEE tested, the parts were operated at the ambient temperature (approximately 25°C) without any overt attempt to either heat or cool the parts. The parts had their thermal pad soldered to a thermal pad on the board to facilitate heat conduction to the board. The output voltage was set to a nominal 1.8V, the switching frequency was 1MHz, and the output capacitance was 750µF. The loading was provided by an electronic load set to either 18A or 24A. The only cooling was through normal conduction and convection from the package to the board and the atmosphere without any forced air flow. Each irradiation was done with normal incidence gold (LET of 86.3MeV•cm²/mg) to a fluence of 1×10^7ion/cm². The parts were monitored before and after each irradiation with the output voltage at load, the input current at load, the input current at zero load, and the input current in shutdown. Working criteria for identifying destructive events in the parameters were changes of 1%, 1%, 3%, and 5% respectively. The results of the testing are presented in Table 5.

Table 5. Destructive Effects Summary for the ISL70002 at 18A and 24A

Units Tested	Current (A)	Schottky GND-LX	PVIN Pass (V)	PVIN Fail (V)
2	18	No	5.5	5.8
1	18	Yes	5.5	5.8
1	24	Yes	5.5	5.8
1	24	Yes	5.5, 5.7	5.8
3	24	Yes	5.5, 5.7	Not tested to fail

All the failures were because of changes in the zero load operating current and the shutdown current. All parts that registered a failure for zero load operating current also registered a failure for the shutdown current. Changes in the zero load operating current were increases from 12% to 38% (63mA to 86mA). The changes in the shutdown current ranged from an increase of 110% to an increase of 810% (4.6mA to 42mA). The other two parameters remained within the 1% criteria. In all cases, the parts remained operating and regulating.

All parts tested at 18A without Schottky and 24A with Schottky passed without detectable damage at PVIN = 5.5V. All the parts taken to failure failed at PVIN = 5.8V. This indicates that for currents above 14A the PVIN must be limited to 5.5V to ensure no damaging SEE effects. In addition, for currents above 18A the GND-LX Schottky is required. In all cases, the thermal management must ensure the junction temperature is limited to 125°C.

7. Revision History

Revision	Date	Description
1.00	Feb 17, 2022	Initial release

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