Heavy-Ion Tests of the Step-Down Switching Regulator MSK5059RH

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Executive Summary

This report details the heavy-ion test experiments performed on the MSK5059RH at the Lawrence Berkeley National Labs (LBNL). The MSK5059RH is manufactured with the Linear Technology RH1959 dice which is packaged and qualified in a hermetic package by MS Kennedy. This power circuit is a 500 KHz monolithic buck mode switching regulator optimized for lower output voltage applications, down to 1.21V output. A 4.5A switch is included on the die along with all the necessary oscillator, control and logic circuitry. The device is packaged in a hermetically sealed 16 pin flatpack and is available with straight or gull wing leads.

Under heavy-ion irradiation, at high bias conditions and high load currents, with the appropriate output filter (an inductance of 6.5 uH and a capacitance of 660 uF), the MSK5059RH showed immunity to Single Event Effects (SEE) up to an LET of 114 MeV.cm^2/mg at elevated temperatures (at least up to junction temperatures of 69.9°C). However, a destructive event was observed on the part when the LBNL cooling plate temperature was not low enough to <u>uniformly</u> maintain the DUT's case at 58°C (eq. at least to a junction temperature of 69.9°C) during irradiation, indicating a potential dependence of the radiation effects on the DUT temperature. We believe this event may have been caused by failure of the thermal interface between the DUT and the test board resulting in a rapid, uncontrolled temperature rise at the die junction. As explained later in this text, the thermal interface material goes through a phase change at or near 60°C. Residue on the board indicates some of the material flowed out of the joint and may have led to catastrophic thermal failure. Once the cooler's temperature was reduced from 20 to 5°C and the DUT's case temperature controlled at 58°C during irradiation at an LET of 114 MeV.cm^2/mg, <u>no destructive events were seen at the same high bias, high load and high junction temperature (at least 69.9°C) conditions</u>. Additional tests are recommended on this part at higher junction temperatures (125°C) when operated in both static and active modes.

To perform SEE tests on power regulators at high temperatures in a vacuum environment, SEE test boards need to be designed to make sure that the die's temperature can be adequately controlled and account for their high power dissipation. In a vacuum environment where there is no thermal convection, only thermal conduction and radiational cooling can be used for temperature control. An improved heat transfer mechanism mainly by conduction is required to maintain the die temperature when operated with high input voltage and high load current. With insufficient thermal design of the test board and poor heat transfer in a vacuum environment, observed events such as current spikes, latchups and destructive events may be the result of thermal overstress and may be misleading to the overall performance of the power device in a radiation environment. In order to obtain reliable test data, Proper board design and temperature control is necessary.

In terms of threshold LET, this data correlates well with the laser test data collected by the NASA-Goddard team [1]. Their report shows a threshold energy that corresponds to an LET of 165MeV.cm^2/mg. I quote <u>*"The laser energy threshold for the dropout events lies approximately between 55 and 110 pJ. These energy levels approximately correspond to heavy-ion LET values of 165 to 330 MeV·cm^2/mg. The*</u>

relatively high LET thresholds are probabilistically not a concern for most space applications". That threshold LET was determined for a filtered output.

However, their measured sensitive cross-section is much smaller than 1% of the total die's area, contradicting our estimated cross-section in heavy-ion beams (about 1%). We believe that the laser tests are more accurate in their cross-section measurements and that the heavy-ion beams are over estimating the correct sensitive cross-section of these parts for the reasons mentioned above (heating of the part by the beam energy, insufficient heat transfer in vacuum, etc.).

Heavy-Ion Tests of the Step-Down Switching Regulator MSK5059RH

1. Overview

This report details the heavy-ion test experiments performed on the MSK5059RH at the Lawrence Berkeley National Labs (LBNL). The MSK5059RH is manufactured with the Linear Technology RH1959 dice which is packaged and qualified in a hermetic package by MS Kennedy. This power circuit is a 500 KHz monolithic buck mode switching regulator optimized for lower output voltage applications, down to 1.21V output. A 4.5A switch is included on the die along with all the necessary oscillator, control and logic circuitry. The device is packaged in a hermetically sealed 16 pin flatpack and is available with straight or gull wing leads. More details are given about these power devices in [2]. This is a 4um technology using exclusively bipolar transistors. The part's block diagram is shown in Fig. 1.

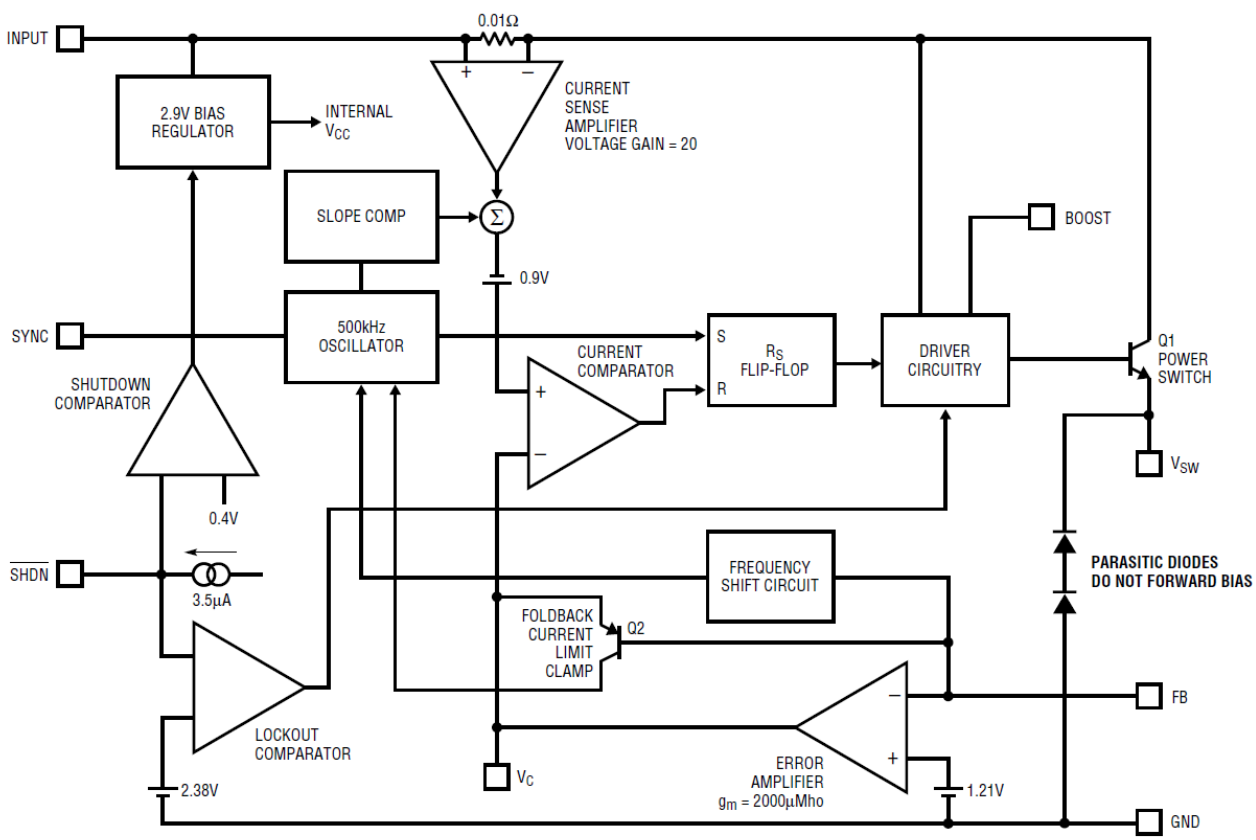

Fig. 1: Block Diagram of the RH1959 DICE

Table 1 summarizes the parts' features and the electrical test equipment.

Table 1: Test and Part's Information

Generic Part Number	MSK5059RH
Package Marking	MSK5059KRH Date Code SN BEO 51651 USA
Manufacturer	M. S. Kennedy Corp./Linear Tech. dice
Lot Date Code (LDC)/Serial Number	0419/1114 , 0089/1043
Quantity tested	2
Dice Dimension	2.032 x 3.505 mm≈ 7.12 mm^2 ≈ 1/14 cm^2
Part Function	4.5A, 500KHz, Step down switching regulator
Part Technology	High Speed Bipolar
Package Style	Hermetically sealed flat-16
Test Equipment	Power supply, digital oscilloscope, multimeter, and computer

1. Test Setup

Custom SEE boards were built for the heavy-ion tests by the MS Kennedy team [3]. Two identical SEE test boards were symmetrically mounted on an aluminum plate used as an adapter to the LBNL cooling plate, as shown in Fig. 2. A thermally conductive, reinforced “S-Class” gap filling material (Gap Pad® 2500S20)[1],was placed between the aluminum adapter and the SEE test board to better conduct the thermal energy between them. To make sure that the Device Under Test’s (DUT’s) temperature is maintained in vacuum and that the part is not excessively heating, we mounted our test board with four of the eight 4-40 screw mounting holes shown in Fig. 3 of the cooling plate.

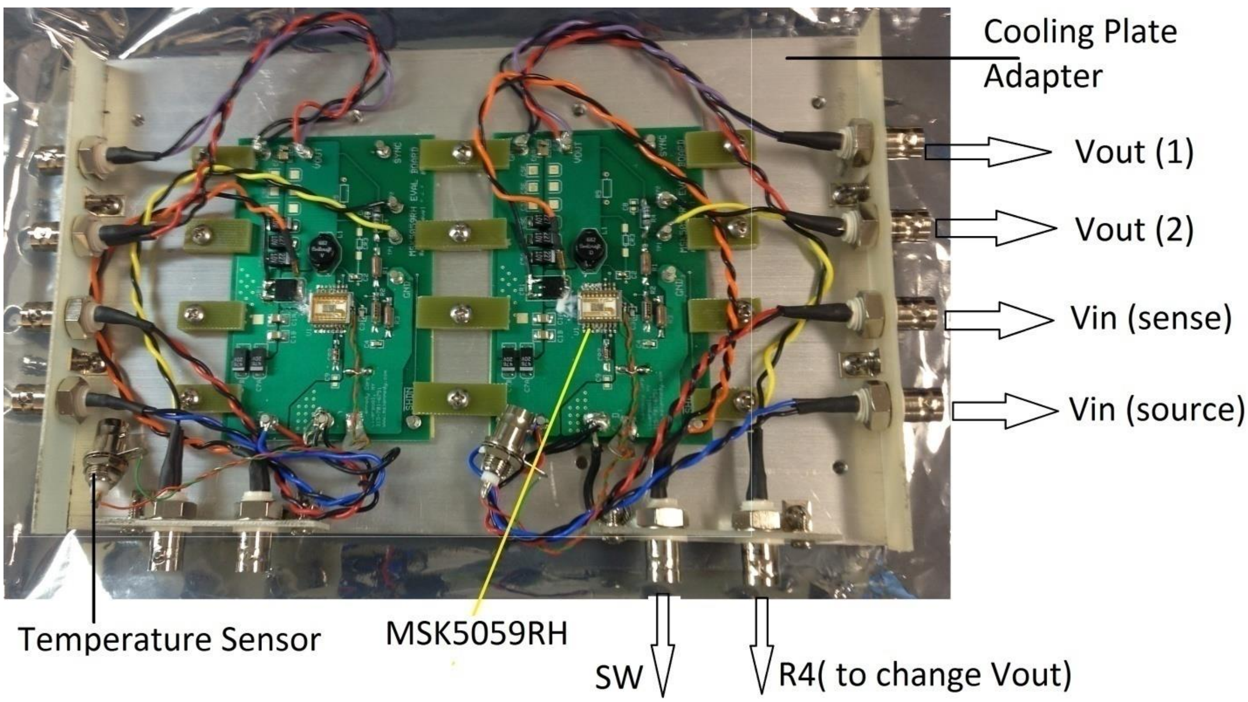

Fig. 2: Photography of the SEE Test Board Mounted on the Cooling Plate Adapter

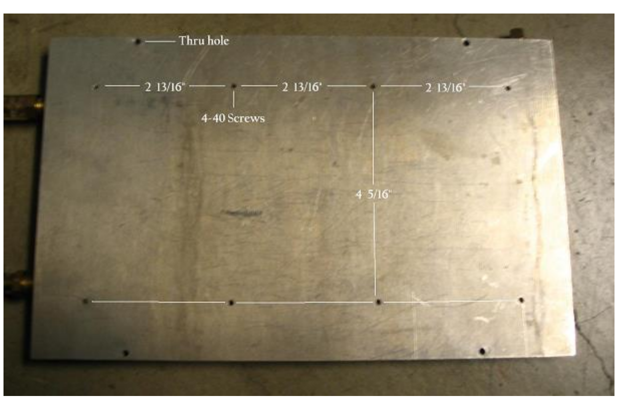

Fig. 3: Photography of the Cooling Plate

Fig. 4: Photography of the Cooling Plate Controller (Temperature is set at 20°C)

[1] The Gap Pad® 2500S20 is readily available from The Bergquist Company.

The cooling plate temperature is set by the controller outside of the vacuum but in the same radiation chamber and can be set down to -30°C and up to 80°C. The controller's display screen provides the coolant's temperature at all times and was set initially at 20°C, as shown in Fig. 4. During the beam runs, we were monitoring the case temperature but not the dice temperature. Hence the test engineer needs to account for additional temperature difference between the dice and the case, which was not measured in vacuum. The temperature difference between the junction of the die and the case is a function of power dissipation multiplied by the thermal resistance $R_{theta\text{-}JC}(\Theta_{JC})$. The case temperature was measured on average at about 35°C when the input voltage (Vin) was at 5V, the output voltage (Vout) at 3.3V and the load current at 1.7A. This value was correlated with a thermocouple. However, when we increased Vin to 16V and the current load to 3.3A, the case temperature increased to 58°C. As the difference in temperature between the case and the cooler increases with the load current and the input voltage, the temperature difference between the case and the die will also increase. The latter was not measured in vacuum; its calculation is provided in Eq.1.

$$T_J = T_C + P_D * \Theta_{JC} \qquad (1)$$

Where: T_J is the junction temperature, T_C the case temperature, P_D the power dissipated in the die and Θ_{JC} the thermal resistance between the die and the case. The calculation of the dissipated power in the die is provided in Eq. 2:

$$P_D = P_{in} - P_{out} - P_{Diode} \qquad (2)$$

Where P_{in}= Vin*Iin,P_{out}= Vout*Iout and P_{Diode} ~= Vf * Iout * (1-Vout/Vin)

Note: a relatively small amount of power is dissipated in other components on the board. That is not considered in this calculation.

In the case where:

T_c = 58°C; V_{in}= 16V; I_{in} = 0.88A; V_{out} = 3.3V; I_{out} = 3.27A, Vf ~= 0.35V and Θ_{JC}= 5°C/W [2]

$\underline{P_D = 2.38\text{W and } T_J = 69.9°\text{C}}$

We normally expect the junction temperature to be lower in air with convection cooling the device as well. While testing in the vacuum, we rely primarily on thermal conduction with a minor amount of radiational cooling. To better maintain the DUT case temperature at about 58°C, we decreased the cooling plate temperature to 5°C. Note that we used a thermal compound (Ultrastick PN 031117) between the DUT and the board. The compound is rated for -40°C to 200°C. It goes through a phase change, which means it melts at 60°C (Note: the phase change temperature may be lower in a vacuum). At that point, it is supposed to flow into any remaining gaps to maximize effectiveness. It is not supposed to flow out of the joint but if excess compound is applied some may flow out. In a vacuum environment small amounts of trapped air in the compound may force it out as it goes through the phase change. Additionally the melting temperature may be lower in the vacuum environment and the surface tension that normally draws the material deeper into the gaps at atmospheric pressure may be low enough to allow it to run out of the gaps more easily when it melts. During the irradiation, the DUT case temperature we were operating at (T_C=58°C) was very close to the compound's melting temperature (60°C). Fig. 5 shows it melted under the DUT and flowed out of the gap. The thermal resistance between the die and the board then increased leading to a higher case temperature than 58°C, loss of thermal interface (compound) and rapidly increasing die temperature. A lower overall coolant temperature was then required to prevent the thermal interface from failing.

In future tests, we plan to:

1. Replace this thermal compound by a non-electrical one which has also a higher melting temperature or by a gap pad as we did between the SEE board and the cooling plate adapter.
2. Monitor the junction temperature by monitoring the current in the internal SYNC diode to have accurate measurement of the die junction temperature.

Fig. 5: Photography of the die with the melting thermal compound under it (in white color)

The difference in temperature from the die junction to the case and the case to the cooler is mainly due to:

1. The thermal resistance of the MSK5059KRH from junction to case; $R_{theta\text{-}JC}$,
2. The efficiency of the heat transfer between the DUT package, the SEE test board, the gap pad and the aluminum adapter mounted on the cooling plate.

As mentioned above, the difference in temperature between the DUT and the cooling controller increases with the increasing power dissipation in the DUT which is directly related to increasing load current and input voltage. The DUT temperature after each run is shown in Table 2. More details about the test facility and the drawing of the cooling plate can be found at: http://cyclotron.lbl.gov/base-rad-effects/heavy-ions/4B-drawings.

Fig. 6 shows the SEE test board schematics. It contains:

- The DUT with open-top (as shown in Fig. 2)
- The filtering caps for the input voltage; AVX PN TAZH476K020L (CWR29JC476K)
- The filtering caps for the output; AVX PN TAZH227K010L (CWR29FC227K)
- The feedback voltage divider (R1, R2 and R4 resistors)
- The error-amplifier RC filter on the Vc voltage control pin

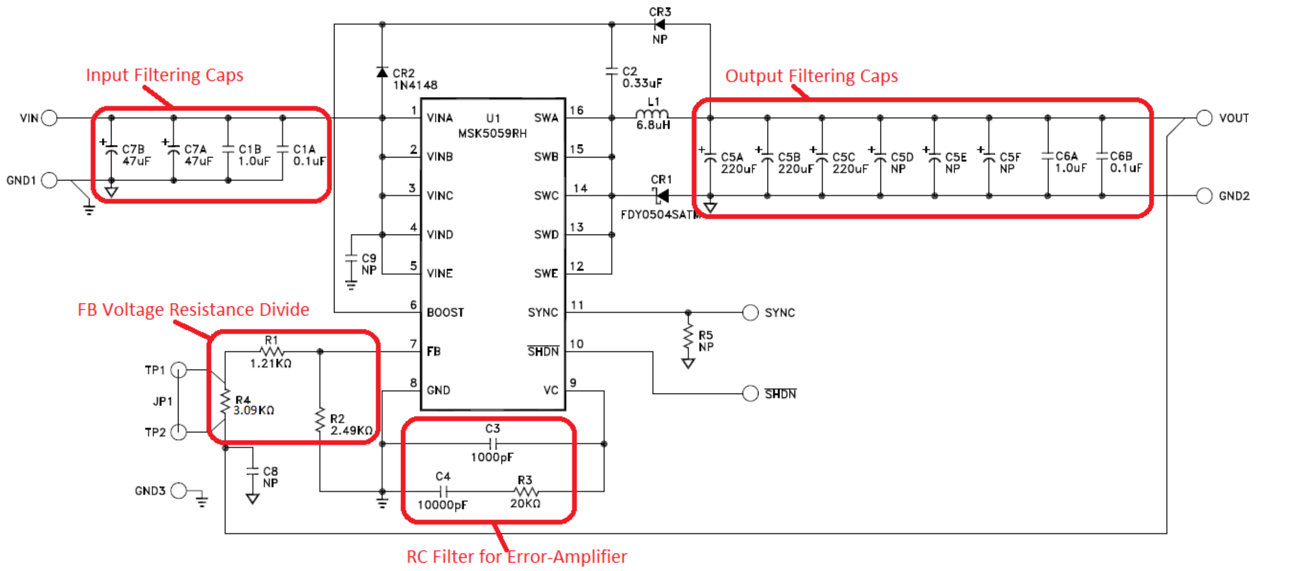

Fig. 6: Block Diagram of the MSK5059RH SEE Test Board

For SEE tests, the board was placed in vacuum as shown in Fig. 7. It is connected with two 50ft long BNC cables to an Agilent power supply (P.S.) (sense and source) and to a Tektronix oscilloscope (DPO 4054 500 MHz, 2GS/s) to view the switch (SW) and the output voltage (Vout) signals, as shown in Fig. 8. This power supply allows the automated logging and storage every 75ms of the voltage and the current input supplies (Vin, Iin), as well as the automation of power-cycles after the detection of a current spike on the input current that exceeds the current limit set by the user. The output pin (Vout) was also connected through a 50ft BNC cable to a resistor load box, ranging from 1 ohm to Mega ohms. To scale the output voltage, we have connected both ends of a decade box to TP1 and TP2 (in parallel to R4 in Fig. 1) also through a long 50ft BNC cable. It allows us to decrease the equivalent resistor value and with it the output voltage. The output current (Iout) was however through a DMM and a current probe connected directly to the scope. Furthermore, we have mounted a JFET on the side of the case and were sensing the DUT case temperature simultaneously during irradiation. As mentioned above, the case temperature was reported after each run in Table 2.

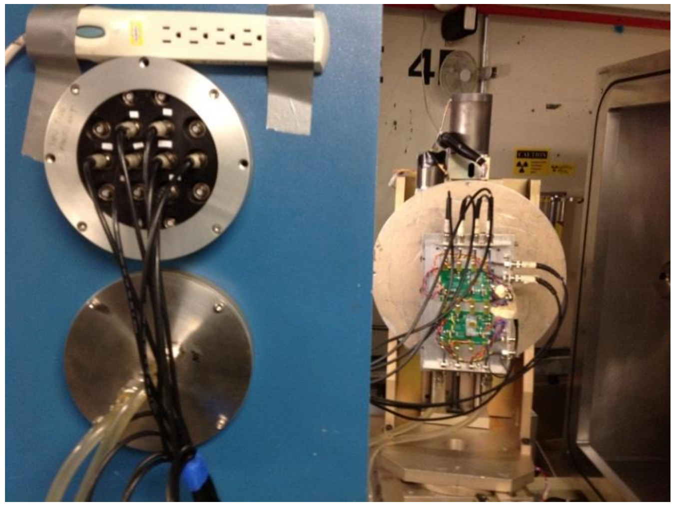

Fig. 7: Photography of the SEE Test Board Mounted on the Cooling Plate and In-Vacuum

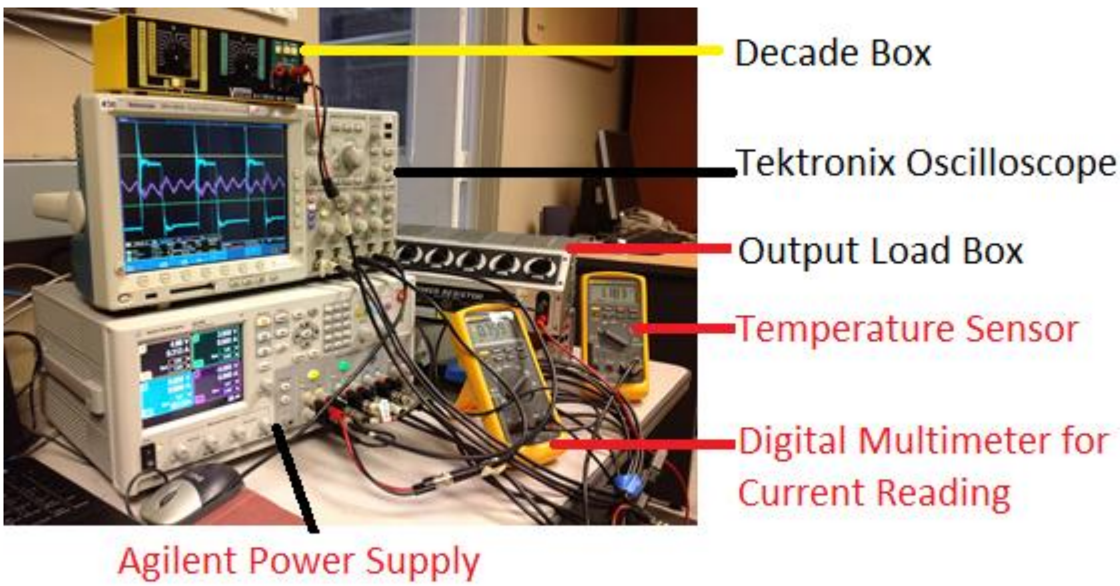

Fig. 8: Photography of the SEE Test Setup placed upstairs of the Vacuum Chamber

2. Heavy-Ion Beam Test Conditions

The MSK5059RH were tested under eight different bias conditions, with the cooling system provided by the LBNL facility. The selected beam energy is 10MeV/nucleon, which correlates with beam ions delivered at a rate of 7.7MHz (eq. to a period of 130 ns). During these130 ns, the ions are generated only within very short pulses that last for 10ns, as shown in Fig. 9. At every pulse of 10 ns, N number of particles per square centimeter, depending on the flux will be irradiating the DUT. The calculation of N is provided in Eq. 3:

$$N = Flux * 130ns \qquad (3)$$

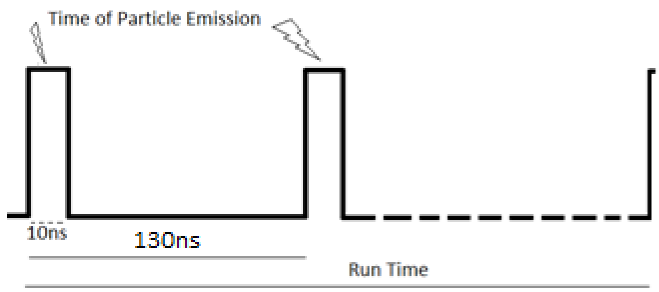

Fig. 9: Particle Emission during a Beam Run at Beam Energy of 10 MeV/nucleon; Emission Frequency = 7.7MHz

For instance if the flux equals 10^4 particles/cm^2/second, the probability (N) of having a particle emitted and striking within a defined square centimeter within a random 10ns active period and even during the entire period of 130 ns is $1.30x10^{-3}$. Multiply that value by the die area to determine the probability of a particle striking the die; $1.30x10^{-3}$ particles/cm^2 * 0.2032cm * 0.3505cm = $9.26x10^{-7}$. On average, one particle per square cm is emitted every 770pulses. We don't know exactly at what pulse this particle will be irradiating the DUT. The random nature of that emission will change the elapsed time between any two consecutive particles. The higher the beam's frequency or the flux; the higher is the likelihood to have more than one particle hitting the DUT in a very short time (within hundreds of nanoseconds). Indeed, the minimum time that is guaranteed by the facility to separate the occurrences of two particles can be as low as 130 ns but the probability of that happening is very low. To avoid overlapping of events, it is important then that the error-events last less than 130 ns or that the flux is much reduced.

In the case of these power devices, some of the DUT's transistors if hit will cause long Single Event Transient (SET) events which will last for microseconds. However, as mentioned above, at a flux of 10^4 particles/cm^2/s, there is no guarantee that two events will not be overlapping within130ns. For events that will last for more than 130 ns for instance, the flux needs to be reduced to avoid having two ion-hits causing the overlapping of two error-events on the DUT's switch output or even increasing the deposited collected charge at each transistor. To make sure that the error-rate calculation is accurate, the flux needs to be reduced until there is a consistency in the number of detected errors with the flux for a given ions' fluence. If that's not the case, the part is subject to multiple hits. There are usually three flux regions: 1) a threshold flux where for any flux below that value, the probability of multiple hits (double or higher) is extremely low and therefore negligible, 2) an instable region where the increase of the flux at a given LET and a given fluence will increase the SEE cross-sections almost linearly, and 3) a plateau or saturation region where the part is saturated meaning that the number of multiple hits won't make any difference anymore as the part has reached its saturation. Measured SEE cross-sections that will correlate best with orbital error-rates in space environment should use a flux that is lower than the threshold flux (region 1). We did not observe any SEE sensitivity in the case of the MSK5059RH and hence no flux dependence. The run fluxes are reported in Table 2.

3. Radiation Test Results

1) SET Events on the SW signal <u>with no Output Voltage Dropout</u>

The MSK5059RH parts were irradiated under eight bias conditions in 36runs. The output current was viewed on the scope by means of a current probe. The raw heavy-ion beam test results are summarized in Table 2, showing SET sensitivities on the output switch line. The SETs were mostly shorter than 1us, and were all filtered by the output RC filter. To detect these SETs, the scope was set to trigger on switching negative pulse widths wider than 2us. Nominally, the SW signal is toggling at 500 KHz (2us period). Depending on the duty cycle (DC≈Vout/Vin), the pulse width (PW) can vary. For instance, for Vin=5V and Vout=3.3V, DC≈66%. In this case, the positive pulse lasts for approximately 80%*2us= 1.3us and the negative pulse lasts approximately 0.7us. By setting, the PW trigger at 2us, we will determine the highest SET cross-section of this part independently of the duty-cycle value and therefore of the bias conditions. The minimum trigger value should usually be variable with the DC value and the bias conditions but that was not done in this case. All trigger conditions were for events that would cause a negative transient at the output if the transient affected the output. None of the conditions look for the possibility of a positive going transient at the output.

Note that the triggering on the switch signal was used only to better understand the part's sensitivity and mostly to select the most suited LC filter to avoid voltage dropouts on the output. In this case, 10 us SETs were observed at high LETs (114 MeV.cm^2/mg). A user of this part should care mostly about the voltage output value (the filtered SW signal). Ideally, radiation-induced SETs on the regulator switch signal should have been counted and their pulse widths measured versus their numbers by an automated tester (for instance based on an FPGA) to allow the calculation of their final orbital error-rates versus the selected filter. This will enable the selection of the most adequate LC filter for a given application based on a trade-off between the orbital error-rate and the most appropriate filter.

We've then run additional measurements while triggering on a 5% output voltage dropout to verify that the used LC filter with an equivalent capacitance of 660uF is sufficient. For instance, in the case where Vout=3.3V, the scope trigger value was at 3.12V (95%*3.3V). During all the beam runs, the scope trigger conditions were reported in Table 2. Fig. 10 and Fig. 11 show two examples of SETs on the SW signal:

1) See figure 10; SET on the SW signal (blue) and an output voltage dropout less than 5% (yellow) of the total output voltage. A very slight decrease in the output current during the SET (green) due to the decrease in voltage across the load resistor; Vin=5V; Vout=1.8V.

2) See figure 11;SET on the SW signal (blue) and an output voltage dropout less than 5% (yellow) of the total output voltage. A very slight decrease in the output current during the SET (green) due to the decrease in voltage across the load resistor; Vin=5V; Vout=3.3V.

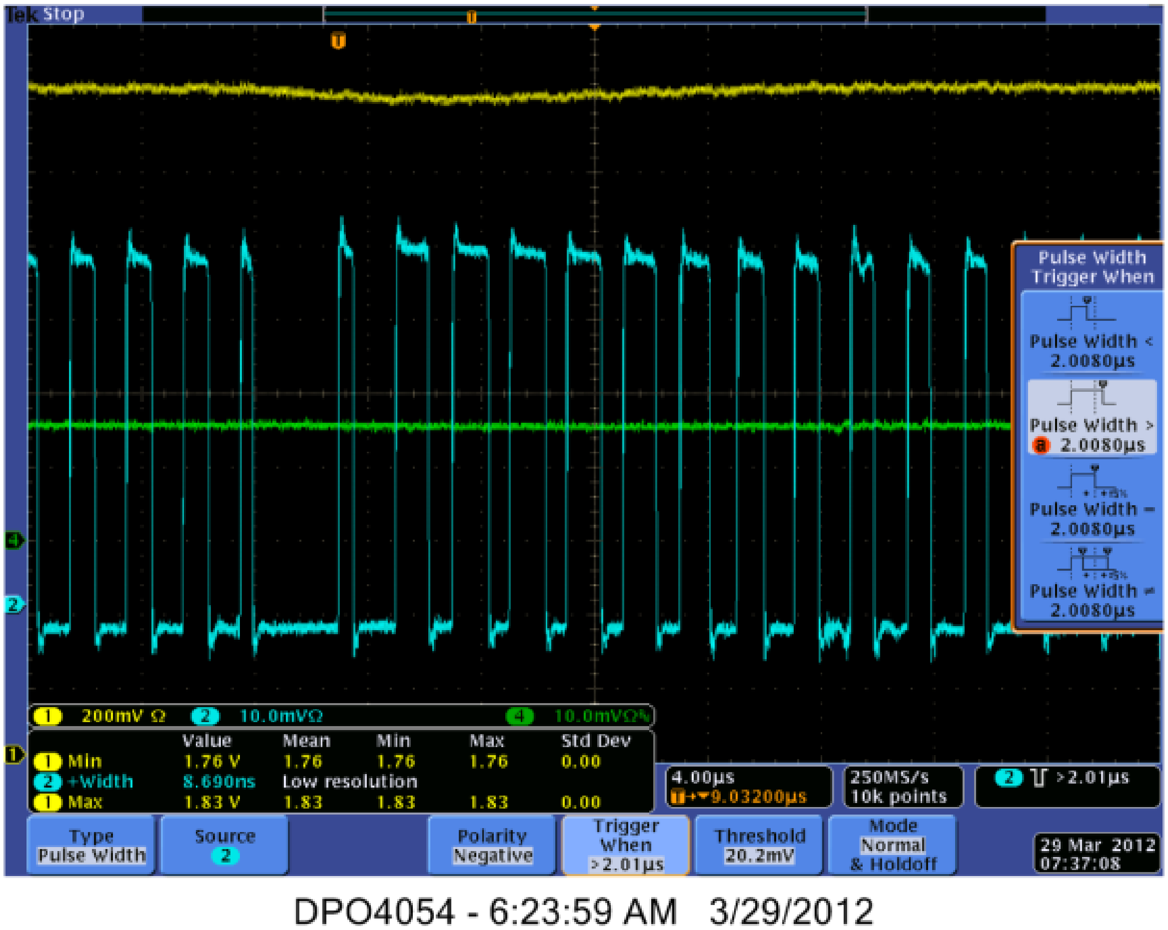

Fig. 10: SET on the SW signal (blue);Vin=5V; Vout=1.8V

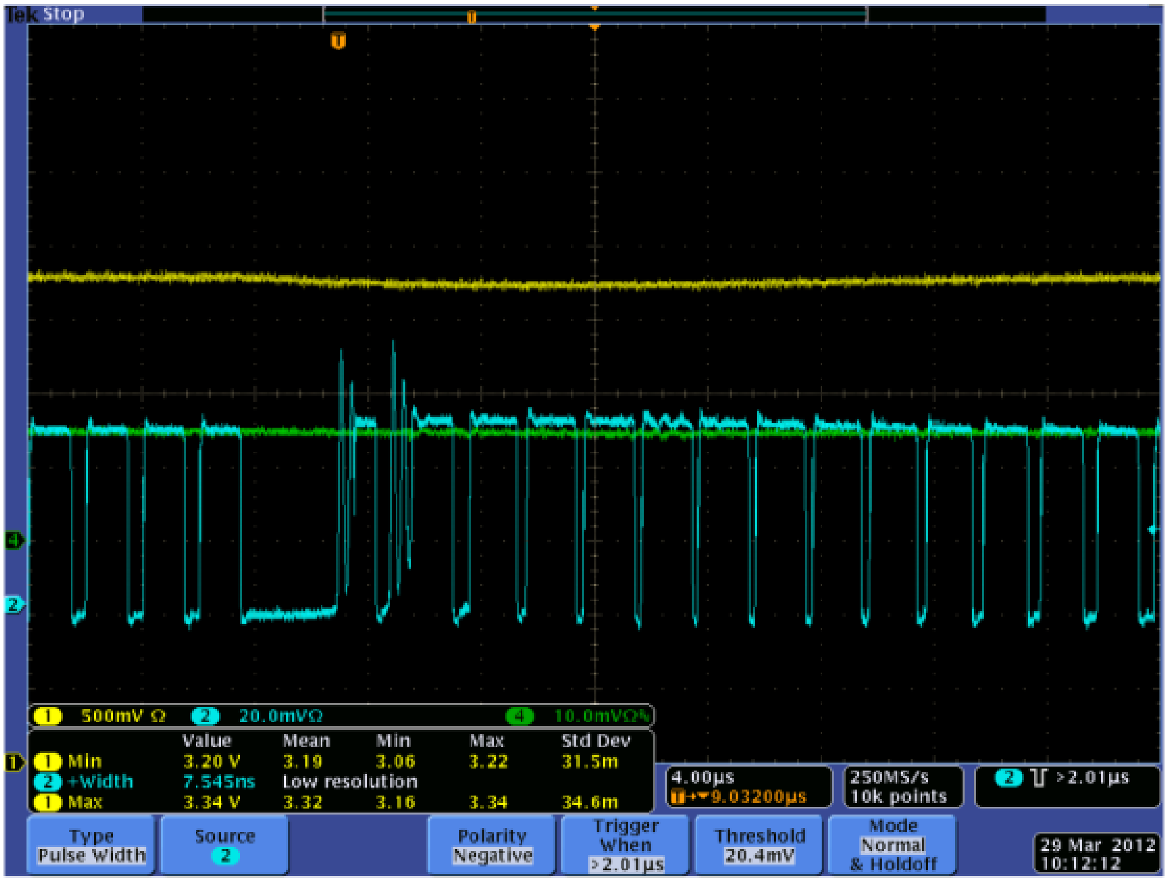

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Fig. 11: SET on the SW signal (blue); Vin=5V; Vout=3.3V

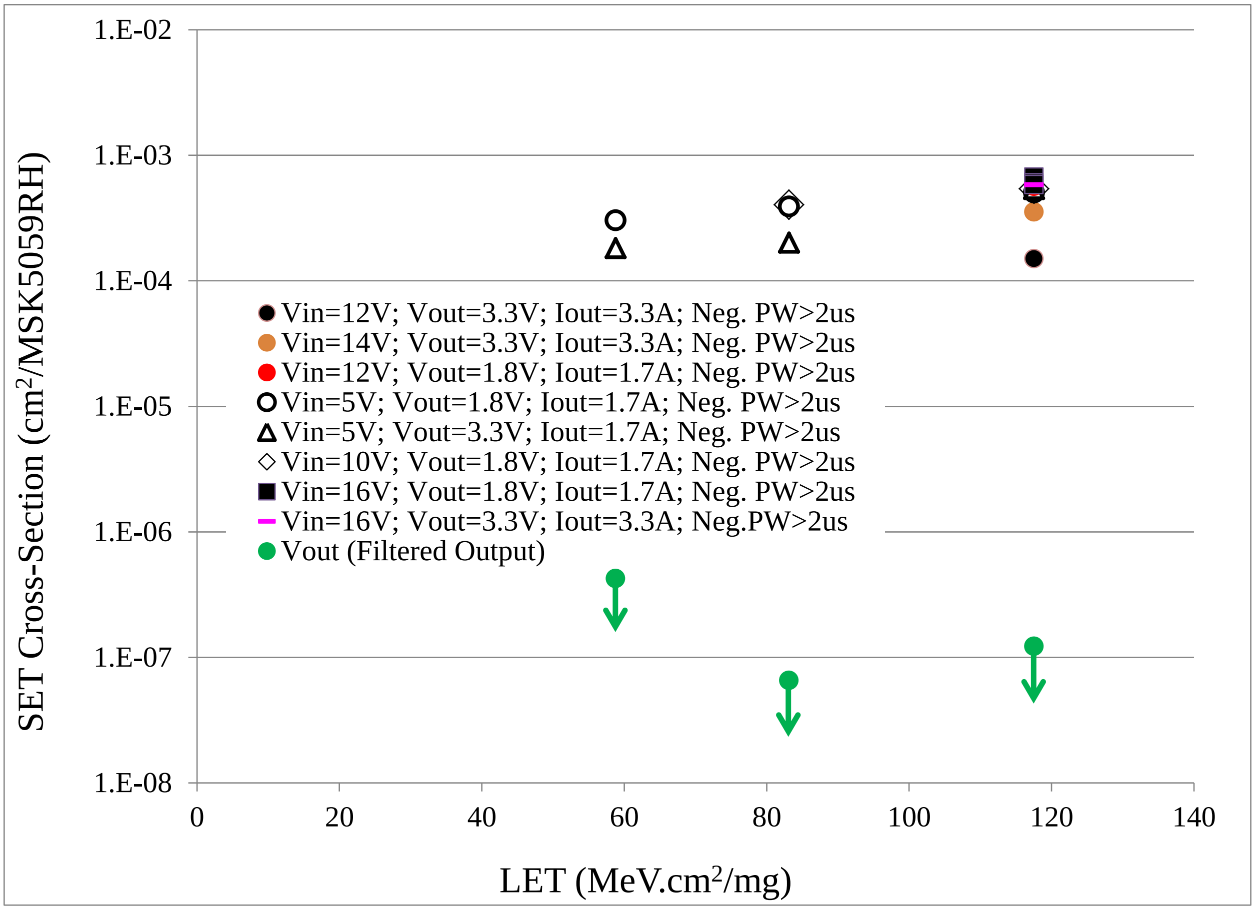

Fig. 12: SET Cross-Sections of the MSK5059RH SW signal vs. the input and output voltages showing **NO VOLTAGE DROPOUTs BELOW 95% ON THE FILTERED OUTPUT SIGNAL(shown in green)**

With the selected filter at the switch output, the test results (green circles in Fig. 12) show no SEE sensitivity at the output voltage up to an LET of 114 MeV.cm^2/mg for input biases up to 16V with Vout equal to 3.3V and Iout equal to 3.3A. Fig. 12 summarizes the SET cross-sections at the different bias conditions. We believe that with better thermal cooling of this part (improved control of the die and the case temperatures); these cross-sections as well as their maximum pulse widths will significantly decrease.

At an LET of 114 MeV.cm^2/mg, the measured limiting cross-section is 6.7x10^{-4} cm^2/die. This means that the sensitive cross-section on the part is about 6.7x10^{-2} mm^2, which is about 1%of the total die's area. This result is contradictory with the laser tests performed by the NASA-GSFC team showing a much smaller sensitive cross-section (much less than 1% of the die's area) than the estimated beam's cross-section. We believe that the laser tests are more accurate in their cross-section measurements and the heavy-ion beams are overestimating the correct sensitive cross-section of these parts for the reasons mentioned above (heating of the part by the beam energy, insufficient heat transfer in vacuum, etc.).

2) *Destructive Event (False Alarm) with a poor heat transfer between the case and board: Operator mistake enhanced in a vacuum radiation environment*

At an LET of 114 MeV.cm^2/mg, when the output current was increased to 3.3A, by reducing the equivalent output resistance (BNC cable and load box) to 1ohm, the part started heating up right after the start of the irradiation and collapsed within seconds in thermal runaway resulting in a destructive event. As shown in Fig. 13, the part was automatically power-cycled by the Agilent P.S., as the MSK5059RH current consumption hit the P.S. current limit that we manually set for the input current. Additional tests are needed to make sure that these events are not due to higher SEE sensitivities at higher temperatures but rather to poor heat dissipation in vacuum. Note that in this configuration, applying16V at the input voltage while connecting the Boost pin to Vin across the capacitor is a violation of the absolute maximum voltage on the Boost pin (30V). In this case, we have applied about 32V on the Boost pin.

Up to that run (85 in Table 2), the cooler's temperature was set at about 20°C and the DUT's temperature at 58°C before irradiation. In the beginning of the run, these events lasted for about 750 ms (Fig. 13). Note that the current spike (from 0.88 to 1.8A in Fig. 13) occurred before the voltage dropout and the case temperature value kept escalating during this run up to 140°C, which most likely led to thermal junction breakdown. At these events, the output voltage dropped below 3.12V (95% of 3.3V). However as the melting temperature (60°C) of the thermal compound between the case and the board was very close to the case temperature at which we were operating (T_C=58°C), it melted under the case, see Fig. 5. The thermal resistance between the case and the board has then increased leading to a case temperature higher than 58°C, thus a lower overall coolant's temperature was then mandatory. We believe that the high case temperature combined with the radiation induced current spikes increased the die junction and case temperatures further, melting the thermal compound. Those events led to thermal runaway and resulted in catastrophic thermal failure of the DUT. Reducing the cooler's temperature was mandatory to avoid that scenario and eliminate these events.

To make sure that these effects are due to excessive heating of the case and consequently of the dice in vacuum, we have switched the ion beam to the second SEE test board, reduced the cooler's temperature to 5°C and waited for a few minutes until the case temperature dropped sufficiently. Because of the lack of time, we did not wait until the DUT's temperature fully stabilized after changing the cooler's temperature. No current spikes or thermal runaways occurred when the cooler's temperature was set at 5°C, which maintained the DUT case temperature between (62°C and 52°C) before and after irradiation.

Therefore, we believe that the observed destructive event in the first SEE board was the result of the thermal compound melting between the case and the board, creating additional thermal isolation between them and die temperature that was much higher than the maximum rated junction temperature. This may have been initiated by radiation-induced current spikes that could have not been promptly recovered by the die (as it should be in a well-designed board and space environment) because of the insufficient heat transfer between the case and the board. This is shown in the beam runs (85, 88 and 97) performed at similar case temperatures (58°C and 52°C) and high voltage and load current conditions. The input current and voltage supplies for these runs are shown in Figs. 13, 14 and 15, respectively. Additional tests in the static mode are recommended to make sure that the part is SEE immune at a junction temperature of 125°C in vacuum.

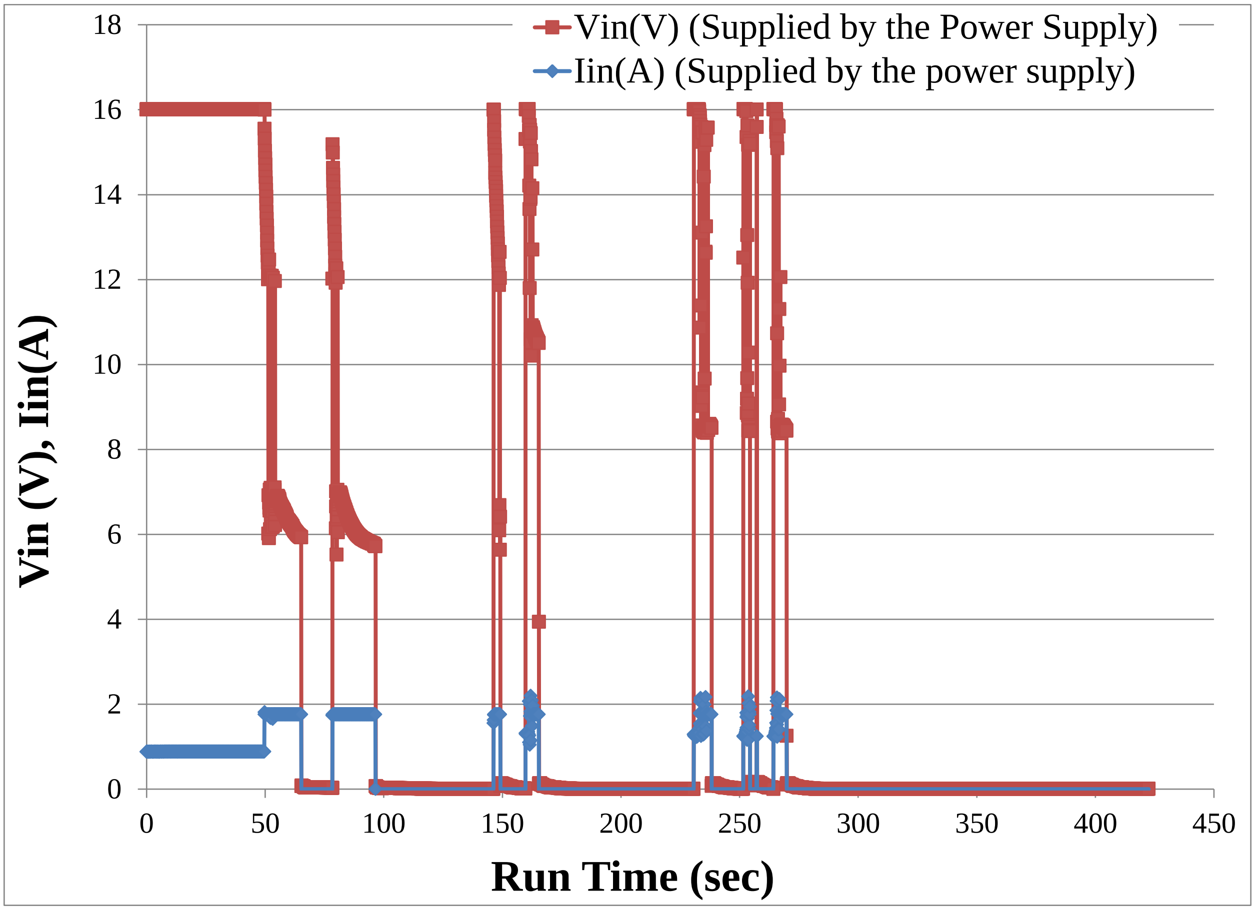

Fig. 13: Plots of the Input Current and Voltage to the Switch Regulator during the run 85
Vin=16V; Vout=3.3V; Iout=3.3A; Cooler Temperature = 20°C; Case Temperature = 58°C

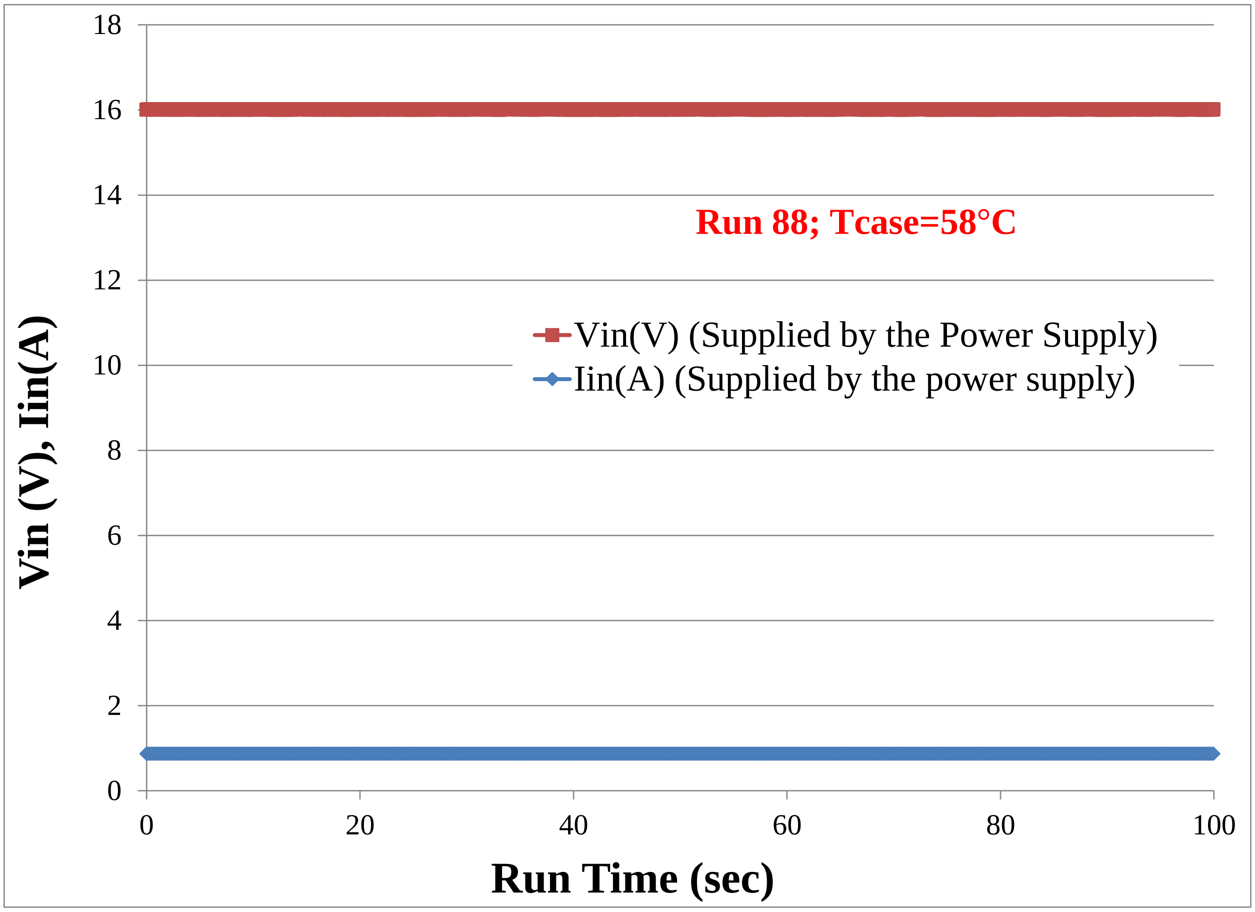

Fig. 14: Plots of the Input Current and Voltage to the Switch Regulator during the run 88
Vin=16V; Vout=3.3V; Iout=3.3A; Cooler Temperature = 5°C; Case Temperature = 58°C

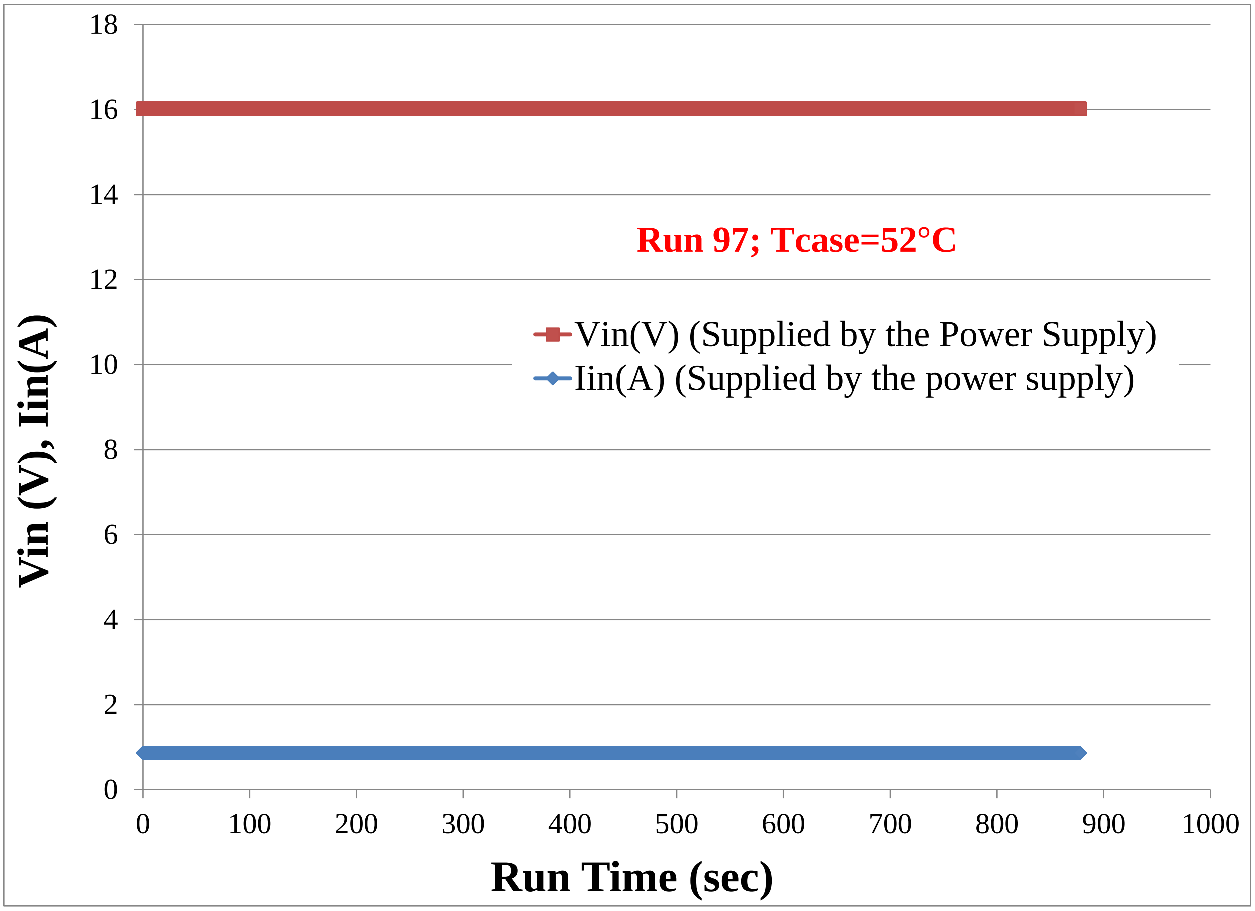

Fig. 15: Plots of the Input Current and Voltage to the Switch Regulator during the run 97
Vin=16V; Vout=3.3V; Iout=3.3A; Cooler Temperature = 5°C; Case Temperature = 52°C

Table 2: Raw Data for the Heavy-Ion Beam Runs

Run	DUT	Cooling Plate Temp.	T_C (Vacuum)	Vin	Vout	Iout	Vout Trigger	%Vout	SW Neg. PW >	Effective Fluence	Maximum Flux	LET	Tilt Angle	Effective LET	TID (Run)	TID (Cumulative)	# SET	# Destructive Event	SET Cross-Section
		°C	°C	V	V	A	V		us	particles/cm2	particles/cm2/s	MeV.cm2/mg	degrees	MeV.cm2/mg	rads (Si)	rads (Si)			cm2/circuit
62	1	20	35	5	1.8	1.7			1.5	4.96E+04	1.26E+03	58.78	0	58.78	4.66E+01	4.66E+01	20	0	4.03E-04
63	1	20	35	5	1.8	1.7			2	8.22E+04	1.47E+03	58.78	0	58.78	7.73E+01	1.24E+02	20	0	2.43E-04
64	1	20	35	5	1.8	1.7			2	1.00E+06	1.70E+03	58.78	0	58.78	9.40E+02	1.06E+03	20	0	2.00E-05
65	1	20	35	5	1.8	0.92			2	1.10E+05	1.50E+03	58.78	0	58.78	1.03E+02	1.17E+03	31	0	2.82E-04
66	1	20	35	5	3.3	1.7			2	1.15E+05	1.58E+03	58.78	0	58.78	1.08E+02	1.28E+03	21	0	1.83E-04
67	1	20	35	5	3.3	1.7	3.12	95%		1.00E+06	3.26E+03	58.78	0	58.78	9.40E+02	2.22E+03	0	0	1.00E-06
68	1	20	35	5	3.3	1.7			2	1.04E+05	1.62E+03	58.78	45	83.13	1.38E+02	2.35E+03	21	0	2.02E-04
69	1	20	35	5	3.3	1.7	3.12	95%		5.01E+06	1.17E+04	58.78	45	83.13	6.66E+03	9.02E+03	0	0	2.00E-07
70	1	20	35	5	1.8	1.7	1.71	95%		5.02E+06	3.99E+04	58.78	45	83.13	6.68E+03	1.57E+04	0	0	1.99E-07
71	1	20	35	5	1.8	1.7			2	5.12E+04	1.52E+03	58.78	45	83.13	6.81E+01	1.58E+04	20	0	3.91E-04
72	1	20	35	10	1.8	1.7			2	4.95E+04	1.56E+03	58.78	45	83.13	6.58E+01	1.58E+04	20	0	4.04E-04
73	1	20	35	10	3.3	1.7			2	4.95E+04	1.40E+03	58.78	45	83.13	6.58E+01	1.59E+04	20	0	4.04E-04
74	1	20	35	10	3.3	1.7	3.12	95%		5.01E+06	2.15E+04	58.78	45	83.13	6.66E+03	2.26E+04	0	0	2.00E-07
76	1	20	35	5	3.3	1.7			2	3.71E+04	4.17E+02	58.78	60	117.56	6.98E+01	2.26E+04	20	0	5.39E-04
77	1	20	35	5	3.3	1.7	3.12	95%		2.02E+06	5.36E+04	58.78	60	117.56	3.80E+03	2.64E+04	0	0	4.95E-07
78	1	20	35	5	1.8	1.7			2	3.95E+04	1.28E+03	58.78	60	117.56	7.43E+01	2.65E+04	20	0	5.06E-04
79	1	20	35	10	1.8	1.7			2	3.86E+04	1.46E+03	58.78	60	117.56	7.26E+01	2.66E+04	20	0	5.18E-04
80	1	20	35	10	1.8	1.7			2	3.52E+04	5.01E+02	58.78	60	117.56	6.62E+01	2.66E+04	20	0	5.68E-04
81	1	20	35	12	1.8	1.7			2	3.54E+04	4.86E+02	58.78	60	117.56	6.66E+01	2.67E+04	20	0	5.65E-04
82	1	20	35	12	3.3	1.7			2	2.77E+04	3.90E+02	58.78	60	117.56	5.21E+01	2.68E+04	20	0	7.22E-04
83	1	20	37	16	3.3	1.7			2	3.14E+04	6.10E+02	58.78	60	117.56	5.91E+01	2.68E+04	21	0	6.69E-04
84	1	20	58	16	3.3	3.27			2	3.48E+04	6.72E+02	58.78	60	117.56	6.55E+01	2.69E+04	21	0	6.03E-04
85	1	20	58-140	16	3.3	3.27	3.12	95%		7.12E+05	2.52E+04	58.78	60	117.56	1.34E+03	2.82E+04	0	1	1.40E-06
86	2	5	57	12	3.3	3.27	3.12	95%		1.00E+06	1.20E+04	58.78	60	117.56	1.88E+03	1.88E+03	0	0	1.00E-06
87	2	5	60	14	3.3	3.27	3.12	95%		1.00E+06	1.10E+04	58.78	60	117.56	1.88E+03	3.76E+03	0	0	1.00E-06
88	2	5	58	16	3.3	3.27	3.12	95%		1.01E+06	2.86E+04	58.78	60	117.56	1.90E+03	5.66E+03	0	0	9.90E-07
89	2	5	57	16	3.3	3.27	3.12	95%		3.50E+05	1.15E+04	58.78	60	117.56	6.58E+02	6.32E+03	0	0	2.86E-06
90	2	5	57	12	3.3	3.27	3.12	95%		1.78E+05	1.12E+04	58.78	60	117.56	3.35E+02	6.65E+03	0	0	5.62E-06
91	2	5	57	12	3.3	3.27	3.12	95%		2.23E+05	3.67E+04	58.78	60	117.56	4.19E+02	7.07E+03	0	0	4.48E-06
92	2	5	57	12	3.3	3.27			2	1.47E+05	1.14E+04	58.78	60	117.56	2.77E+02	7.35E+03	22	0	1.50E-04
93	2	5	57	14	3.3	3.27			2	7.16E+04	1.17E+04	58.78	60	117.56	1.35E+02	7.49E+03	22	0	3.07E-04
94	2	5	50	14	3.3	3.27			2	6.09E+04	1.55E+04	58.78	60	117.56	1.15E+02	7.60E+03	21	0	3.45E-04
95	2	5	50	14	3.3	3.27			2	4.84E+04	4.40E+03	58.78	60	117.56	9.10E+01	7.69E+03	21	0	4.34E-04
96	2	5	52	16	3.3	3.27			2	6.84E+04	1.34E+03	58.78	60	117.56	1.29E+02	7.82E+03	40	0	5.85E-04
97	2	5	52	16	3.3	3.27			10	1.00E+06	6.19E+03	58.78	60	117.56	1.88E+03	9.70E+03	20	0	2.00E-05

Long BNC cable (1 Ohm)	Energy Cocktail 10MeV/nucleon	Ion=Xe

4. Summary

This report details the heavy-ion test experiments performed on the MSK5059RH at the Lawrence Berkeley National Labs (LBNL). Under heavy-ion irradiations, at high bias conditions and high load currents, with the appropriate output filter (an inductance of 6.5 uH and a capacitance of 660 uF), the MSK5059RH showed immunity to Single Event Effects (SEE) up to an LET of 114 MeV.cm^2/mg at elevated temperatures (at least up to junction temperatures of 69.9°C). However, a destructive event was observed on the part when the LBNL cooling plate temperature was not low enough to uniformly maintain the part's case at 58°C (eq. at least to a junction temperature of 69.9°C) during irradiation, indicating a potential dependence of the radiation effects on the part's temperature. We believe this event may have been caused by failure of the thermal interface between the DUT and the test board resulting in a rapid, uncontrolled temperature rise at the die junction. As explained previously in this text, the thermal material goes through a phase change at or near 60°C. Residue on the board indicates some of the material flowed out of the joint and may have led to catastrophic thermal failure. Once the cooler's temperature was reduced from 20 to 5°C and the DUT's case temperature controlled at 58°C during irradiation at an LET of 114 MeV.cm^2/mg, no destructive events were seen at the same high bias, high load and high junction temperature (at least 69.9°C) conditions. Additional tests are recommended on this part at higher junction temperatures (125°C) when operated in both static and active modes.

To perform SEE tests on power regulators at high temperatures, SEE boards need to be designed to make sure that the die's temperature can be adequately controlled and account for their high power dissipation, especially in vacuum environment. An improved heat transfer mechanism mainly by conduction is required to maintain the die temperature when operated with high input voltage and high load current in a vacuum environment where there is no thermal convection, only thermal conduction and radiational cooling can be used for temperature control. With insufficient thermal design of the test board design and poor heat transfer in a vacuum environment, observed events like current spikes, latchups and destructive events may be the result of thermal overstress and may be misleading to the overall performance of the power device in a radiation environment.

In terms of threshold LET, this data correlates well with the laser test data collected by the NASA-Goddard team [1]. Their report shows a threshold energy that corresponds to an LET of 165 MeV.cm^2/mg. I quote *"The laser energy threshold for the dropout events lies approximately between 55 and 110 pJ. These energy levels approximately correspond to heavy-ion LET values of 165 to 330 MeV·cm^2/mg. The relatively high LET thresholds are probabilistically not a concern for most space applications*". That threshold LET was determined for a filtered output.

However, their measured sensitive cross-section is much smaller than 1% of the total die's area (7.12 mm^2), contradicting our estimated cross-section in heavy-ion beams (about 1%). We believe that the laser tests are more accurate in their cross-section measurements and that the heavy-ion beams are overestimating the correct sensitive cross-section of these parts for the reasons mentioned above (heating of the part by the beam energy, insufficient heat transfer in vacuum, etc.).

References:

[1]Dakai Chen, Ted Wilcox, "Pulsed-laser Test Report of the MSK5059RH Switching Regulator", NASA GoddardRadiation Effects & Analysis Group, http://radhome.gsfc.nasa.gov/radhome/RadDataBase/RadDataBase.html

[2] MS Kennedy DataSheet: http://www.mskennedy.com/documents/5059RHrg.pdf

[3] MS Kennedy Demo Board: http://www.mskennedy.com/documents/MSK5059RHEvalBoardAppNoteRevA.pdf