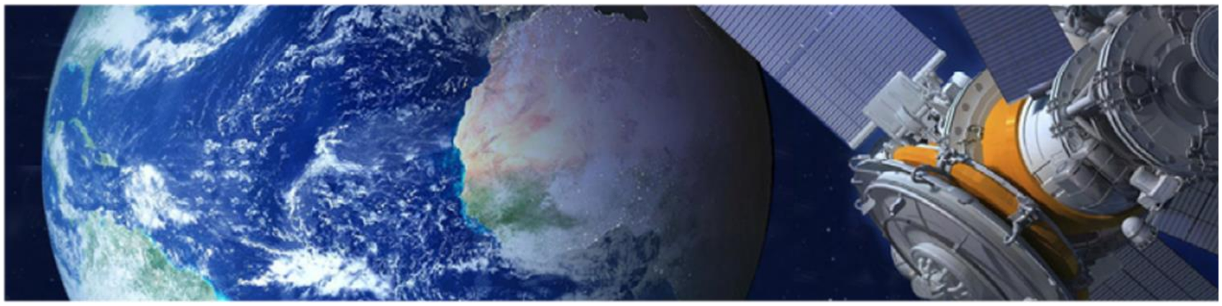

Single Event Effect Report

LMX2615-SP 40MHz to 15 GHz Wideband Synthesizer

Report for April 3rd 2018 test with PG 1.1

May 3 rd 2018, SNAK006

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Single Event Effect Report LMX2615-SP 40MHz to 15 GHz Wideband Synthesizer

1 Abstract

Single Events Effect (SEE) is reported on LMX2615-SP PG1.1. This device is a high performance fully integrated wideband synthesizer capable of generating frequencies up to 15 GHz. The device is immune to radiation and will not latch up with an effective LET=121.28 MeV.Cm^2/mg with Au ions at 45 degrees incidence angle. Single Event Functional Interrupt (SEFI) was observed with Au ions at LET=85.78 MeV.Cm^2/mg while in SPI mode. However, the device will not SEFI with Xe ions at an effective LET=86.19 MeV.Cm^2/mg . We do not have an explanation for this contradictory result. The device has Single Event Upset (SEU). We estimate the upset rate to be 4.95e-4 event/month while about 90% of the event last less than 15 nsec with LET=58.78 MeV.Cm^2/mg

2 Introduction

Texas Instruments' LMX2615-SP is a high performance 15 GHz wideband synthesizer targeted for space applications. Single event effect (SEE) on this integrated circuit are tested and analyzed in this report. The product revision and description is provided along with the test method. Results and analysis are provided for single event latch up (SEL), single event functional interrupt (SEFI) and single event upset (SEU). We first start with a definition of terms used in this report.

3 Terms and Definitions

For more details on these definitions, refer to [1] .

- SEE = Single Event Effect
- SEL = Single Event Latch up
- SEFI = Single Event Functional Interrupt
- SEU –Single Event Upset
- SET = Single Event Transient
- Cross section = Number of events per unit fluence.
- LET = Linear Energy Transfer
- Effective LET = LET/cos(angle)
- PCB = Printed Circuit Board
- FIB = Focused Ion Beam
- FOM = Figure of merit
- PLL = Phase Locked Loop
- VCO = Voltage controlled Oscillator

4 Product under Test

4.1 Description

The LMX2615-SP is a high performance wideband phase lock loop (PLL) with integrated voltage controlled oscillator (VCO) and voltage regulators that can output any frequency from 40 MHz and 15 GHz without a doubler, which thus eliminates the need for ½ harmonic filters. The VCOs on this device covers an entire octave so the frequency coverage is complete down to 40 MHz. The high performance PLL with a figure of merit of -236 dBc/Hz and high phase detector frequency can attain very low in-band noise and integrated jitter. Figure 1 shows a functional block diagram.

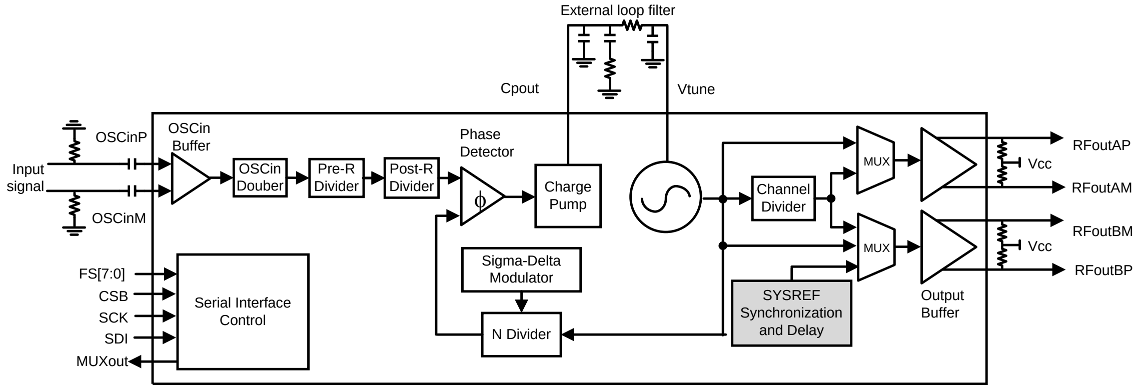


Figure 1. LMX2615-SP functional block diagram.

The LMX2615-SP allows users to synchronize the output of multiple instances of the device. This means that deterministic phase can be obtained from a device in any use case including the one with fractional engine or output divider enabled. It also adds support for either generating or repeating SYSREF (compliant to JESD204B standard), making it an ideal low-noise clock source for high speed data converters. This device is fabricated in Texas Instruments' advanced BiCMOS process and will be available in a 64 pin CQFP ceramic package. Detailed information can be obtained from the data sheet of the LMX2615.

4.2 Device Revision

Device Information: The device used for this radiation testing is LMX2615-SP. The die revision is PG 1.1.

5 Test Method

5.1 Test Facility

All tests were conducted on April 3rd 2018 at the Berkeley National Laboratory 88-inch Cyclotron. [2] We used cave 4B with the 10 AMeV cocktail beams to expose the integrated circuit with heavy ion at the calibrated Linear Energy Transfer (LET). We used the different Ion available (see Figure 2) as well as the angle of incidence to produce the required effective LET. Each experiment was logged capturing all required parameters to facilitate post processing and later calculations. Figure 4 shows the entrance to cave 4B.

Ion	Cocktail (AMeV)	Energy (MeV)	Z	A	Chg. State	% Nat. Abund.	LET 0°	LET 60° (MeV/mg/cm2)	Range (Max) (µm)
B	4.5	44.90	5	10	+2	19.9	**1.65**	3.30	78.5
N	4.5	67.44	7	15	+3	0.37	**3.08**	6.16	67.8
Ne	4.5	89.95	10	20	+4	90.48	**5.77**	11.54	53.1
Si	4.5	139.61	14	29	+6	4.67	**9.28**	18.56	52.4
Ar	4.5	180.00	18	40	+8	99.6	**14.32**	28.64	48.3
V	4.5	221.00	23	51	+10	99.75	**21.68**	43.36	42.5
Cu	4.5	301.79	29	63	+13	69.17	**29.33**	58.66	45.6
Kr	4.5	378.11	36	86	+17	17.3	**39.25**	78.50	42.4
Y	4.5	409.58	39	89	+18	100	**45.58**	91.16	45.8
Ag	4.5	499.50	47	109	+22	48.161	**58.18**	116.36	46.3
Xe	4.5	602.90	54	136	+27	8.9	**68.84**	137.68	48.3
Tb	4.5	724.17	65	159	+32	100	**77.52**	155.04	52.4
Ta	4.5	805.02	73	181	+36	99.988	**87.15**	174.30	53.0
Bi*	4.5	904.16	83	209	+41	100	**99.74**	199.48	52.9
B	10	108.01	5	11	+3	80.1	**0.89**	1.78	305.7
O	10	183.47	8	18	+5	0.2	**2.19**	4.38	226.4
Ne	10	216.28	10	22	+6	9.25	**3.49**	6.98	174.6
Si	10	291.77	14	29	+8	4.67	**6.09**	12.18	141.7
Ar	10	400.00	18	40	+11	99.6	**9.74**	19.48	130.1
V	10	508.27	23	51	+14	99.75	**14.59**	29.18	113.4
Cu	10	659.19	29	65	+18	30.83	**21.17**	42.34	108.0
Kr	10	885.59	36	86	+24	17.3	**30.86**	61.72	109.9
Y	10	928.49	39	89	+25	100	**34.73**	69.46	102.2
Ag	10	1039.42	47	107	+29	51.839	**48.15**	96.30	90.0
Xe	10	1232.55	54	124	+34	0.1	**58.78**	117.56	90.0
Au*	10	1955.87	79	197	+54	100	**85.76**	171.52	105.9
He*	16	43.46	2	3	+1	0.00013	**0.11**	0.22	1020.0
N	16	233.75	7	14	+5	99.63	**1.16**	2.32	505.9
O	16	277.33	8	17	+6	0.04	**1.54**	3.08	462.4
Ne	16	321.00	10	20	+7	90.48	**2.39**	4.78	347.9
Si	16	452.10	14	29	+10	4.67	**4.56**	9.12	274.3
Cl	16	539.51	17	35	+12	75.77	**6.61**	13.22	233.6
Ar	16	642.36	18	40	+14	99.600	**7.27**	14.54	255.6
V	16	832.84	23	51	+18	99.750	**10.90**	21.80	225.8
Cu	16	1007.34	29	63	+22	69.17	**16.53**	33.06	190.3
Kr	16	1225.54	36	78	+27	0.35	**24.98**	49.96	165.4
Xe*	16	1954.71	54	124	+43	0.1	**49.29**	98.58	147.9
N	30	425.45	7	15	+7	0.370	**0.76**	1.52	1370.0
O	30	490.22	8	17	+8	0.04	**0.98**	1.96	1220.0
Ne	30	620.00	10	21	+10	0.27	**1.48**	2.96	1040.0
Ar	30	1046.11	18	36	+17	0.337	**4.87**	9.74	578.1

Figure 2. Available beams with the 10 A MeV (used ions in yellow)

We conducted our test in vacuum using a motorized integrated positioning system. Angles are tracked with the system and captured in the log file. A camera system in the ion beam axis enables the user the position the circuit in the beam axis. Figure 3 shows such a view.

The control room is located right above the radiation area and relatively short cable (> 5 m) can be used to connect the test equipment and the device under test.

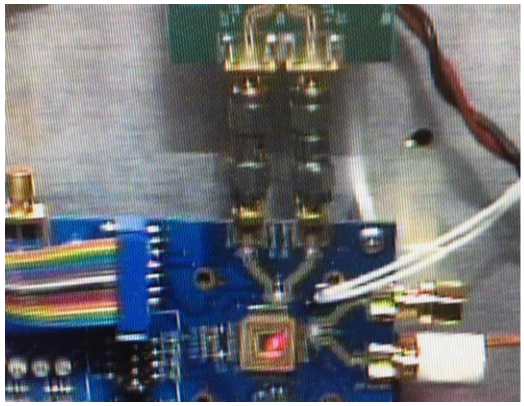


Figure 3. Camera system in the ion beam axis to position the device under test

Figure 4. Entrance to cave 4B at the Cyclotron 88 inch in Berkeley.

5.2 Evaluation PCB for LMX2615-SP

The LMX2615EVM-CVAL PCB was used for radiation testing. It provides in a compact format all the functions needed for testing including the ability as an option to supply power on each pin separately so current can be monitored on a per pin basis. Figure 5 shows a PCB used with the lid removed on the ceramic package.

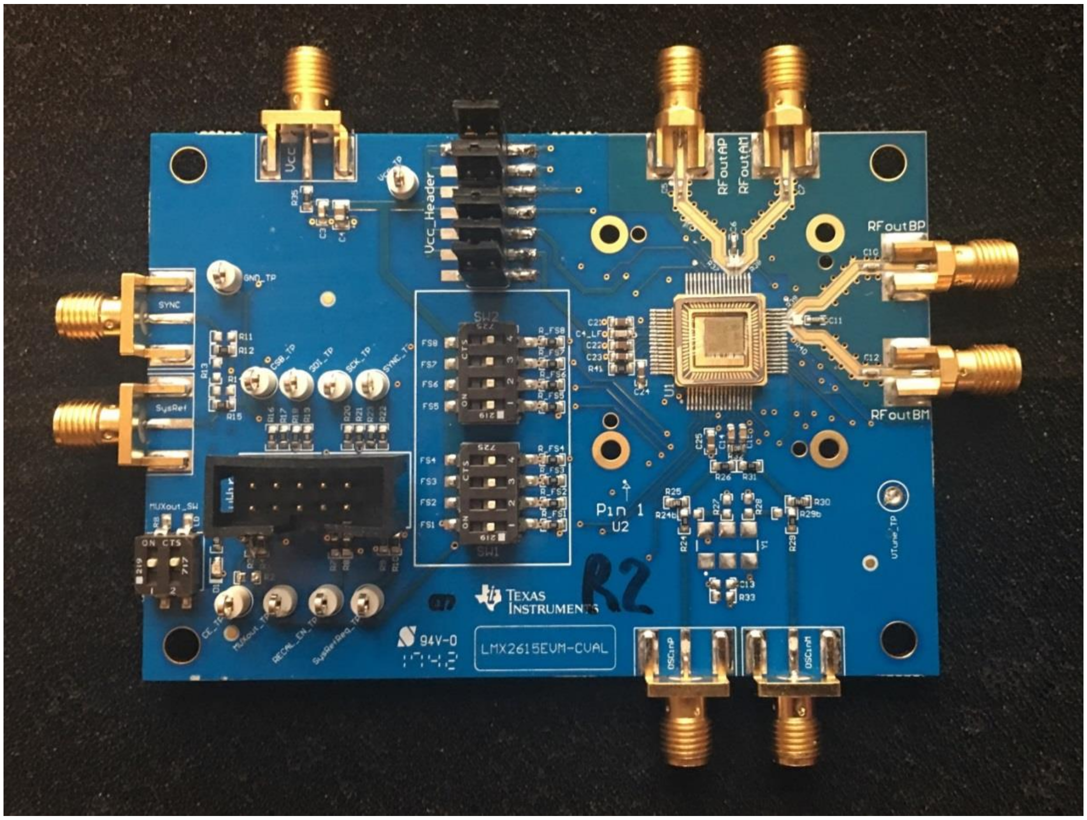


Figure 5. PCB used for radiation testing with lid removed on ceramic package.

5.3 Test capabilities

We configured the setup so that we could enable the following test capabilities:

- Individual power supply voltage and current control on all five supply pin: VccDIG(11), VccCP(21), VccMASH(25), VccBUF(34) and VccVCO2(41)&VccVCO(57).
- Signal generator based reference with differential signal driving the OSCin input
- Remote pin mode control unit
- Serial mode including register read back.
- Output with Balun
- Spectrum Analysis
- Oscilloscope with deep capture and Tektronix FastFrame feature.
- Temperature monitoring with thermocouple and Resistive heater

5.3.1 Equipment

Equipment for testing:

- Oscilloscope Tektronix DPO7354 3.5 GHz;40 GS/s
- Spectrum Analyzer Agilent E4440 26.5 GHz
- Signal generator R&S SMA 100 A 6 GHz
- Power supply Agilent E3632A
- Ammeter Agilent 34401A
- Thermometer Omega with type K thermocouple probe

5.3.2 Setup

Radiation testing was performed using the setup described in Figure 7 . Each power supply current was monitored with an ammeter and captured with an automation routine to capture and save current values. Figure 6 shows the actual PCB mounted on a jig for stable placement in front of the ion beam.

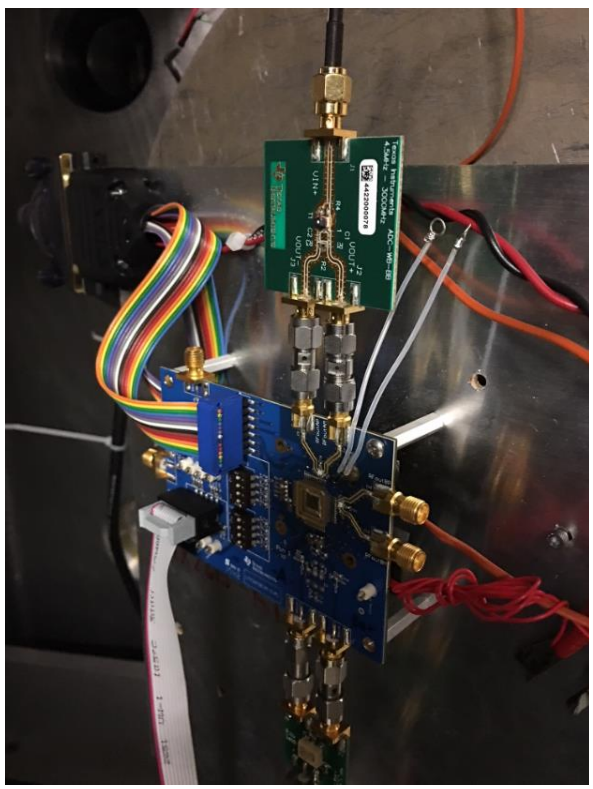


Figure 6. PCB mounted on the motorized jig.

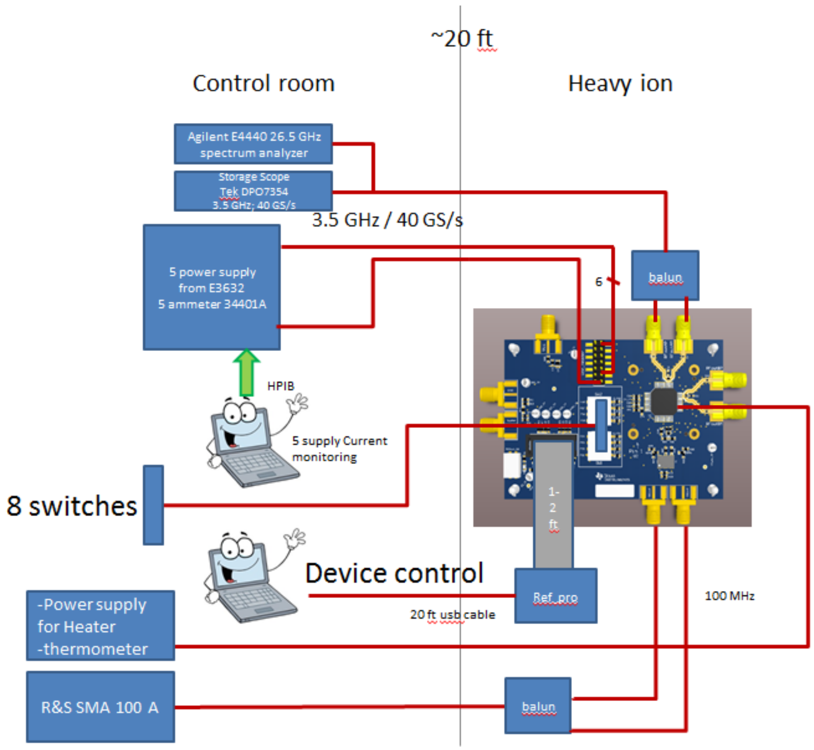


Figure 7. Block diagram of the measurement setup for radiation testing

6 Test Results

The LMx2615-SP was test for SEL, SEFI and SEU.

6.1 Single Event Latchup (SEL)

In this test we placed the device in a normal configuration (SPI and PIN mode) and under heavy ion and monitored current on each supply to see if any of the supply current will rise and remain high, an indication of latch up. We raised the rail voltage to 3.6 V and maintained the back of the PCB where the device is mounted at 125C as a worst case situation. This is the best place to inject heat with the lowest thermal resistance to the circuits.

Table 1 (results) and Figure 9 (current profile for each supply) summarize the SEL test performed on LMX2615-SP with the key results obtained. **The device will not latch up with Au beam and effective LET of 121.28 MeV.cm^2/mg.** Detailed current profile requires automation and 5 separate power supplies. A picture of the configuration can be found in Figure 8.

For test run KDS12, there are 2 observations: (1) The VCO experienced a few spikes. This is obviously as a results of the VCO being hit by ions. (2) The MASH current changes up and down by 2 or 3 mA. While we think this is not anything like a latch up, we currently do not have an explanation for this small phenomena.

For test run KDS15, we noticed the current on the MASH to increase by 2-3 mA around step 32 and then did not come back down. We do not have an explanation for this at this point.

For test run KDS16, the VCO has multiple current increase but always come back down. The higher current is NOT limited by the power supply. This is obviously the results of the VCO being hit by ions.

For test run KDS21, we also see the mash current changing up and down by 2-3 mA.

Table 1. LMX261-SP SEL summary

Test ID*	Power supply [V]	IC Temp [C]	Beam/LET [Mev.cm^2/mg]	Incidence angle [deg]	Effective LET [Mev.cm^2/mg]	Latch up conclusion	Device configuration
KDS1	3.6	room	Au/85.76	0	85.76	NO	Pin mode 5 Oscin=100MHz RFout=300MHz
KDS12	3.6	125	Au/85.76	45	121.28	NO	Pin mode 5 Oscin=100MHz RFout=300MHz
KDS15	3.6	125	Xe/58.78	45	83.13	NO	Pin mode 7 Oscin=100MHz RFout=1200MHz
KDS16	3.6	125	Xe/58.78	45	83.13	NO	Pin mode 6 Oscin=100MHz RFout=1000MHz
KDS21	3.6	room	Xe/58.78	47	86.19	NO	SPI mode Oscin=100MHz RFout=300MHz

*Test in blue have a current capture profile shown.

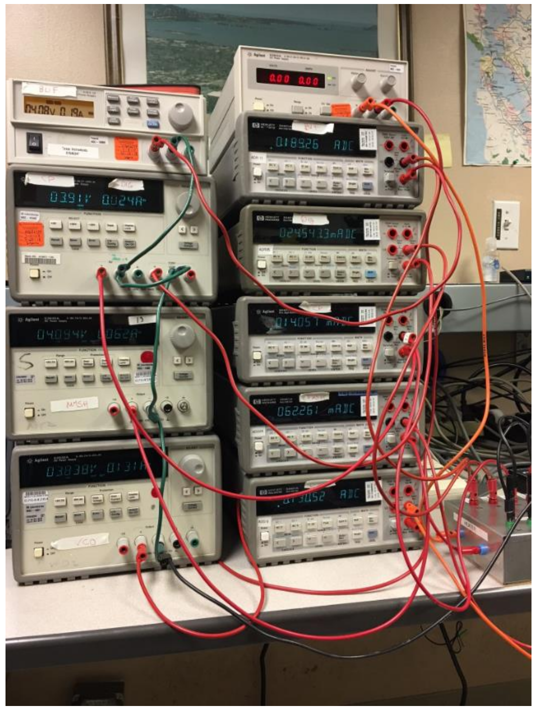
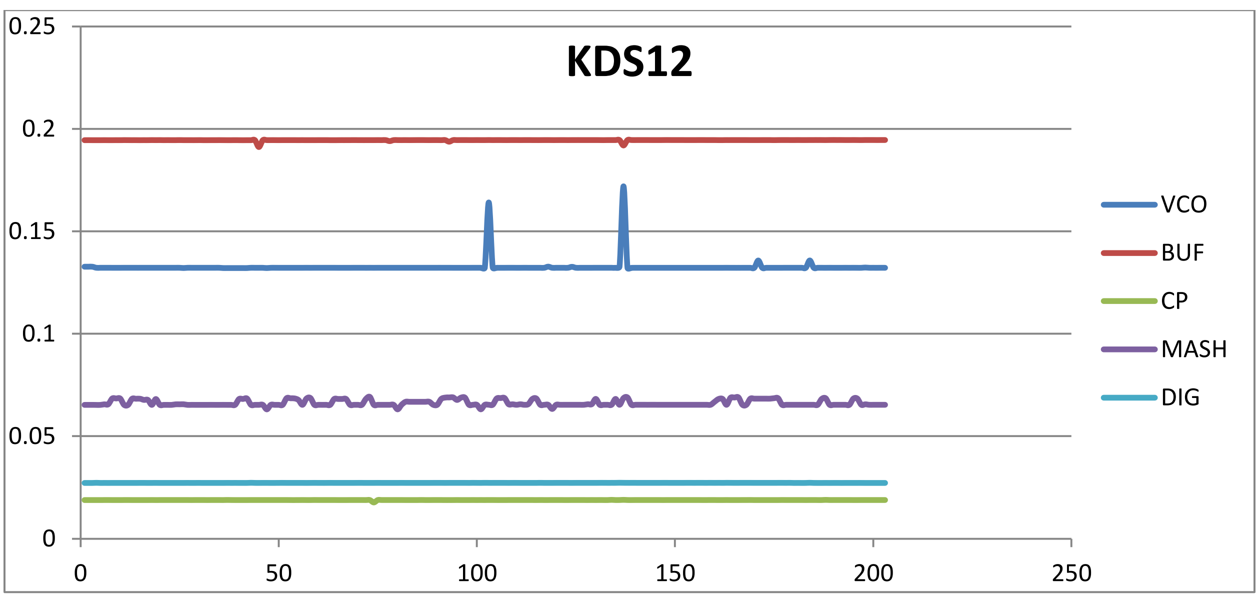
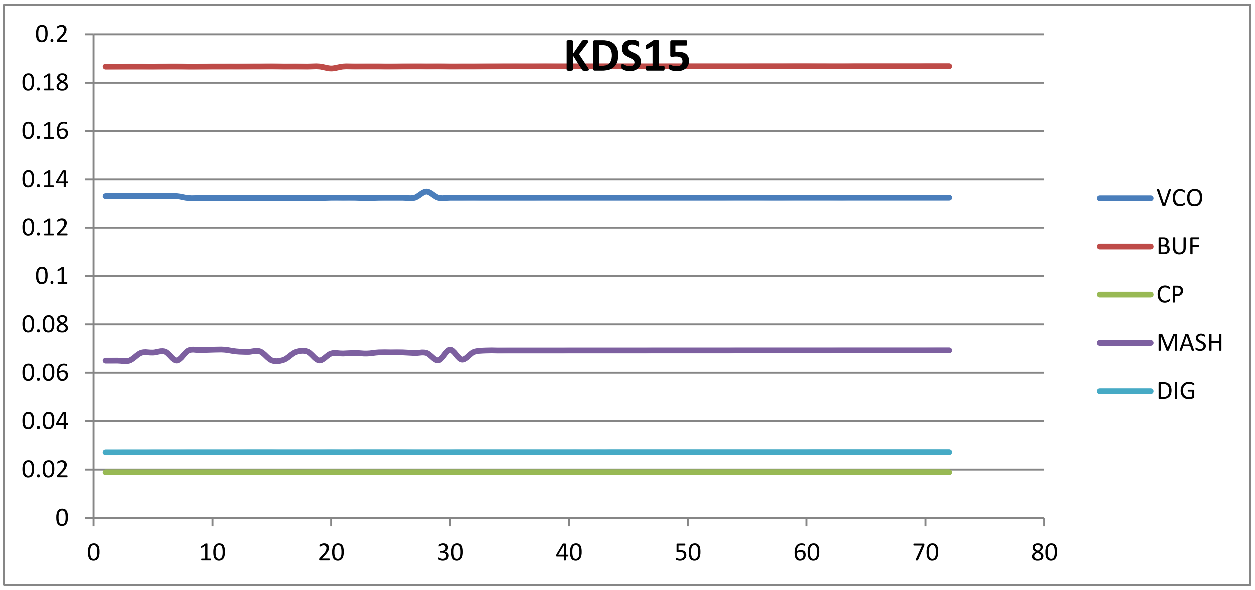


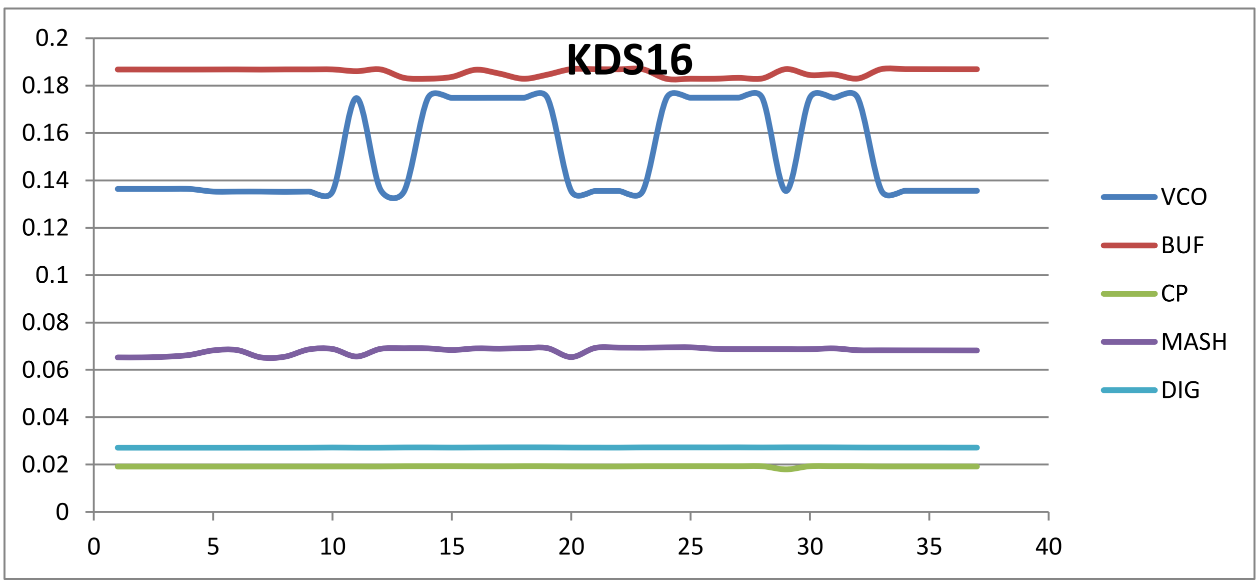
Figure 8. Power supply configuration for LMX2615-SP radiation test.



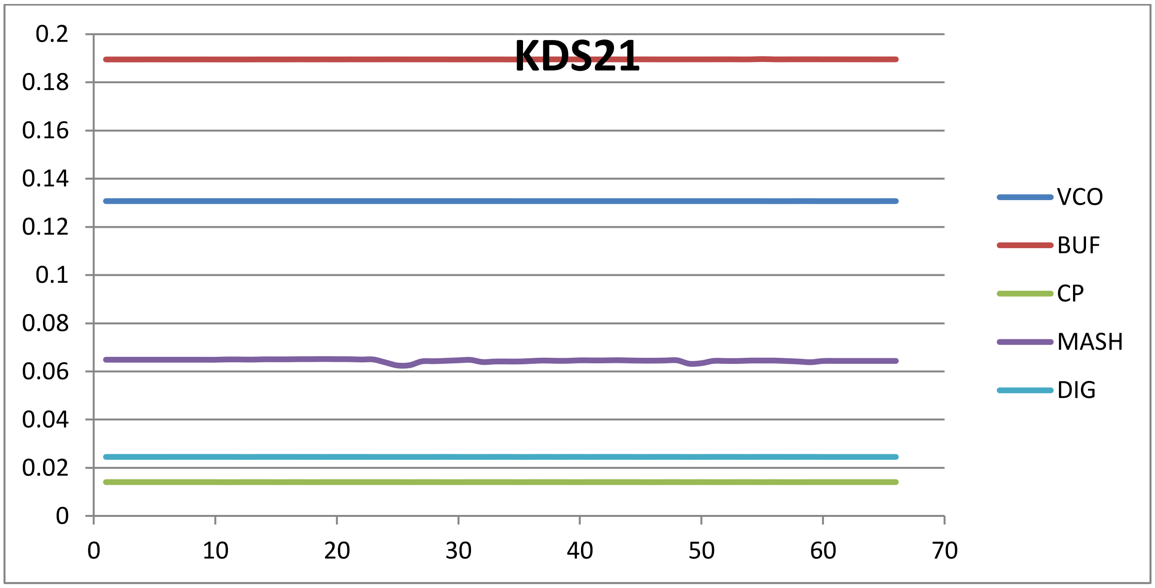
(KDS12 above)



(KDS15 above)



(KDS16 above)



(KDS21 above)

Figure 9. Current (Ampere) profile during each radiation experiment with BLUE test ID summarized in Table 1. All axis are: vertical in [A] and horizontal in uncalibrated steps.

6.2 Single Event Functional Interrupt (SEFI)

This section of the radiation test make sure the device functionality is not changed on a permanent basis neither its register are corrupted or changed. We used Xe and Au ions beam so we can sweep the LET from 58.78 to 120 . Results are summarized in Table 2.

Table 2. SEFI results.

Experiment ID	Ions/LET	Incidence angle	Effective LET	SEFI	Device configuration
KDS2	Au/85.76	0	85.76	yes	SPI mode
KDS21	Xe/58.78	47	86.19	no	SPI mode
KDS1	Au/85.76	0	85.76	no	PIN mode
KDS14	Au/85.76	45	121.28	yes	SPI mode
KDS12	Au/85.76	45	121.28	no	PIN mode

We make the following observations from the table above:

- With comparable effective LET, the device will SEFI with Au but NOT with Xe. We did not see SEFI in PG1.0 in but we never used Au as ions. The effective LET is the metric used and the ions used should not be a factor. We see the impact of the ions on SEFI and we do not have an explanation at this point.

- The device will NOT SEFI with AU ions when PIN mode is used to configure the device. We do not have an explanation for this at this point.

Figure 10 shows the comparison of register read back of the device before and after test run KDS21. There are no changes in registers.

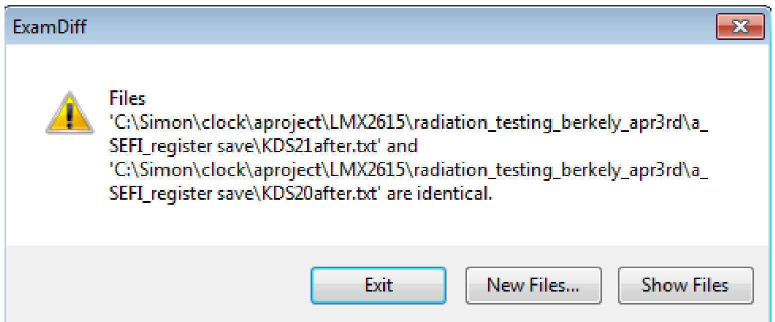


Figure 10. Register comparison of LMX2615-SP for test run KDS21 with LET=86.19.

6.3 Single Event Upset (SEU)

We will divide the analysis of the SEU into two sections. We will perform a statistical analysis of the SEU using the Weibull distribution ([3] , [4]) and a figure of merit (FOM) estimating the number of events per month [5] . In the second section, we will show the statistical duration profile of the upset for 2 levels of LET.

6.3.1 Single Event Upset Statistical Analysis

The Weibull distribution can be found in equation (1).

$$F(L) = A \cdot \left(1 - \exp\left\{-\left(\frac{L - L_0}{W}\right)^s\right\}\right); L > L_0 \qquad (1)$$

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

We will set L_0 to 0 and W to 100. A and s will be optimized to fit data.

The figure of merit (FOM) is calculated with equation (2).

$$FOM = 30 \cdot 200 \cdot \frac{\sigma_{limit}}{{L_{0.25}}^2} \tag{2}$$

Where:

- σ_{limit} is the limiting cross-section
- $L_{0.25}$ is the LET at 25% of the limiting cross-section
- The factor 30 is used to scale the FOM to a month.

The cross section of the available data is found in Table 3 and plotted in Figure 11.

Table 3. Available measured results of the cross section

Experiment ID	Errors [#]	Fluence [ions/cm^2]	Cross section [cm^2] (Error/Fluence)	LET [MeV.cm^2/mg]
KDS26	8	1e7	8.0e-7	0.89
KDS25	20	1e7	2.0e-6	2.19
KDS24	65	1e7	6.50e-6	9.74
KDS23	95	7.89e6	1.20e-5	30.86
KDS22	94	6.62e6	1.42e-5	45.25
KDS18	90	4.52e6	1.99e-5	58.78
KDS9	46	1.19e6	3.87e-5	85.76
KDS13	31	9.75e5	3.18e-5	121.28

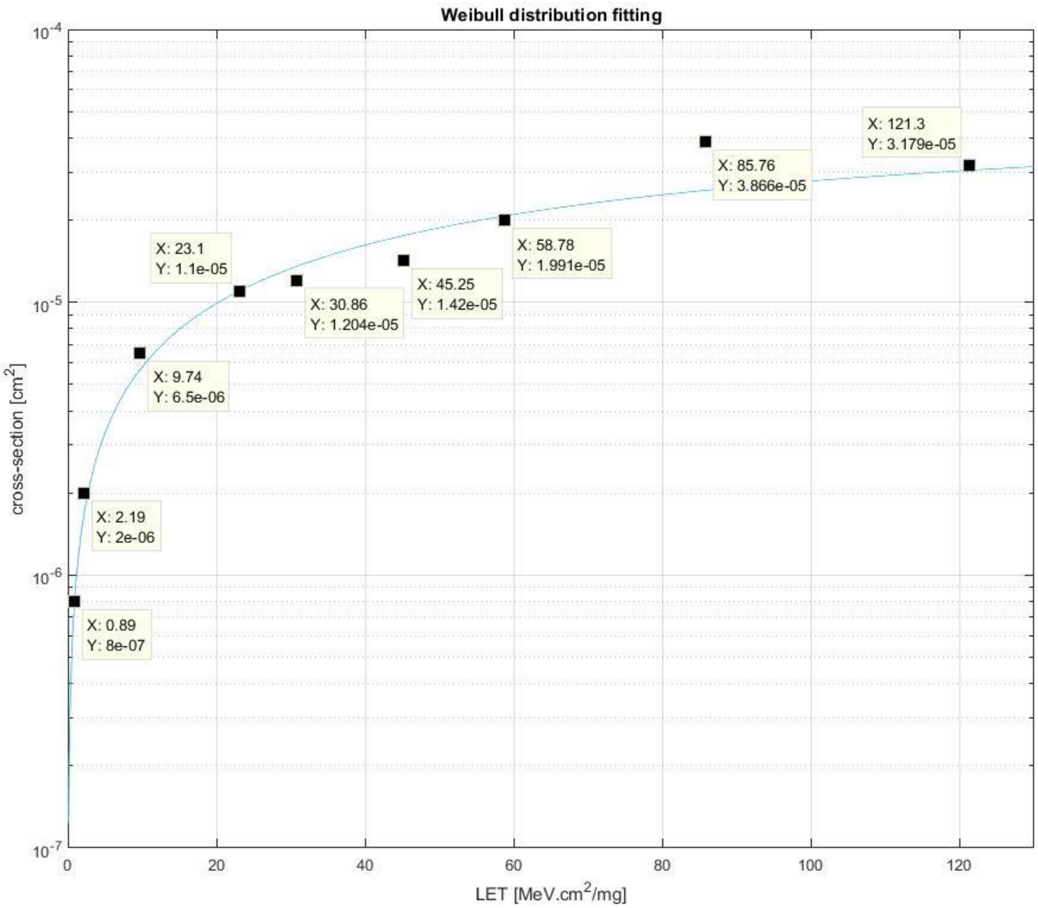


Figure 11. 8 measured cross sections as a function of the LET with fitted Weibull distribution (s=0.85 , A=4.4e-5).

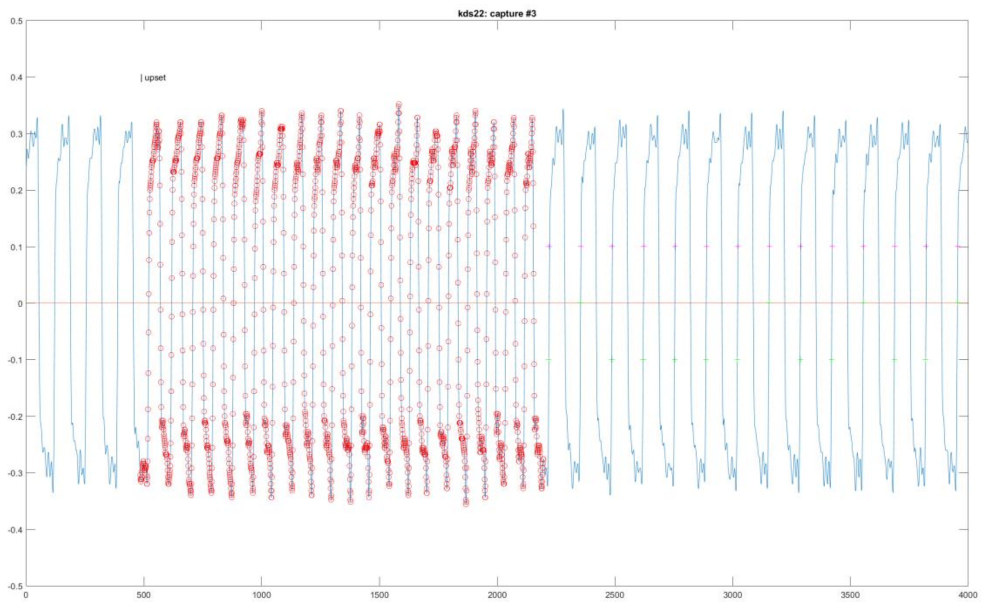
The figure of merit for this distribution is calculated in equation (3).

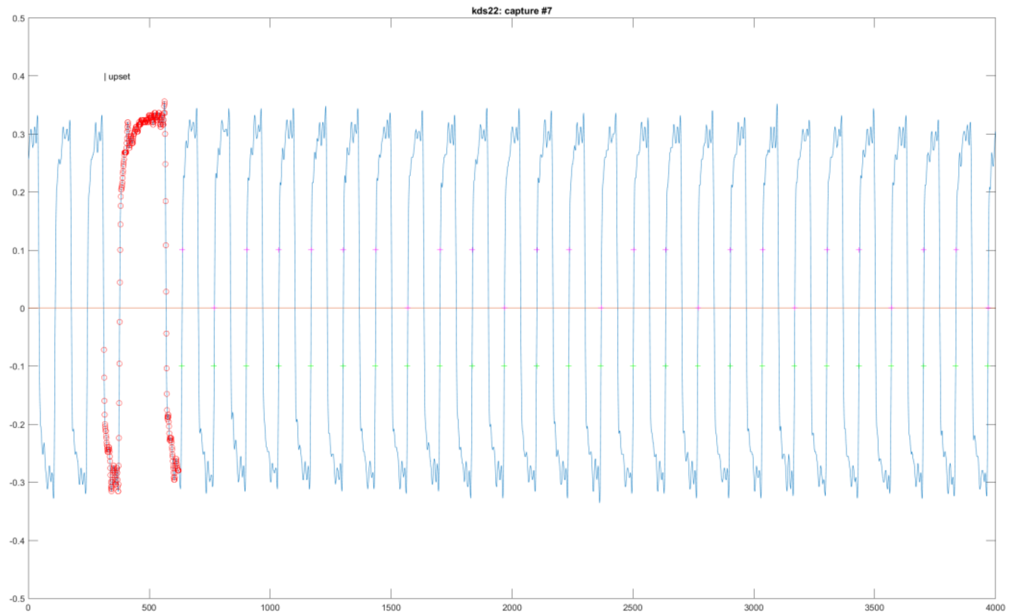
$$FOM = 30 \cdot 200 \cdot \frac{4.4e{-5}}{23.1^2} = 4.95\text{e-4 event/month} \quad (3)$$

6.3.2 Single Event Upset Signature

In this section we make an attempt to describe the upset capture by the Tektronix DPO7354 Fast Frame Feature. We captured 100 events for each run. We display 3 (of the 100 captured) of them selected to be representative of the upset we observed of the dataset. We also made a reasonable estimate of the disturbance time seen on the output and we calculated a distribution of this time.

We start with the upset signature seen with an LET=45.25 MeV.cm^2/mg with KDS22 test run.





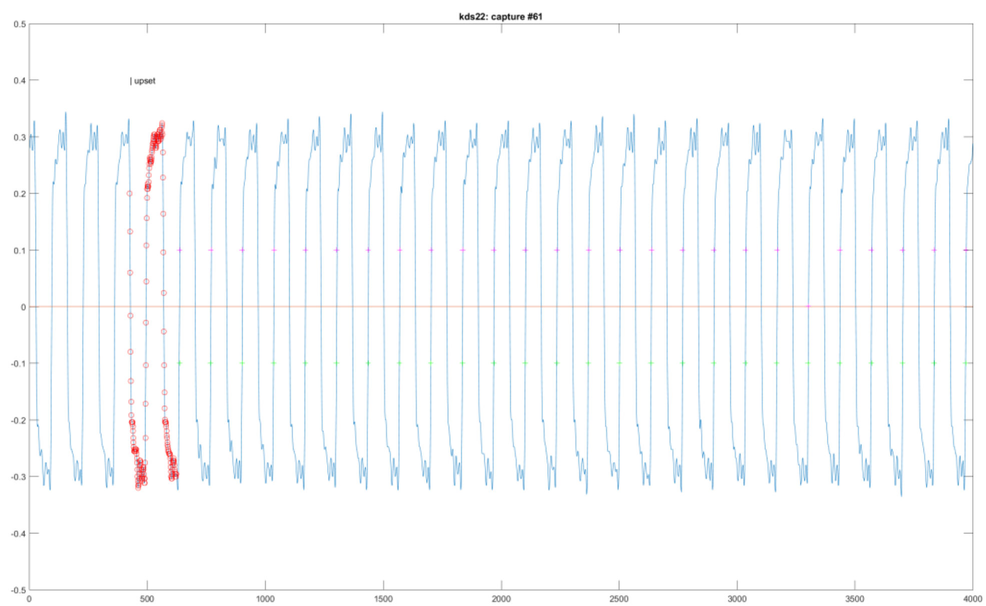


Figure 12.Upset waveform signature at LET=45.25 (KDS22). 3/100 selected to be representative of the upset profile. (Vertical axis in V and horizontal axis in sample point with a sampling time of 25psec)

The distribution of the upset time can be found in Figure 13(b). We can see that about 90% of the upset will last less than 15 nsec based on the Tektronix measurements capture. We are not able to see very fine transitory in the PLL with this measurement technique. In both time sequences, notice some capture last the entire frame of 100 nsec. This means the device upset is lasting on multiple capture of the FastFrame trigger feature of the oscilloscope. We count these captures as one event or upset in our FOM calculations. The upset time for this event will be a minimum of 600 nsec as the upset last for 6 captures.

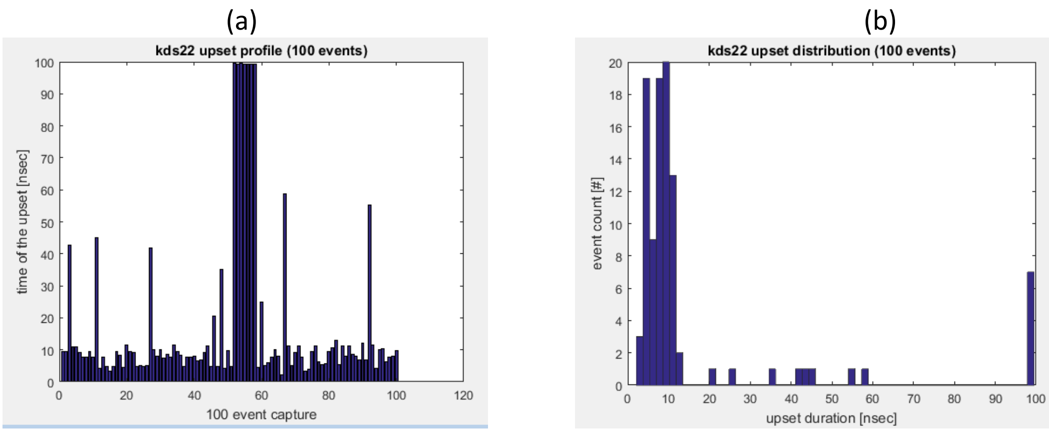
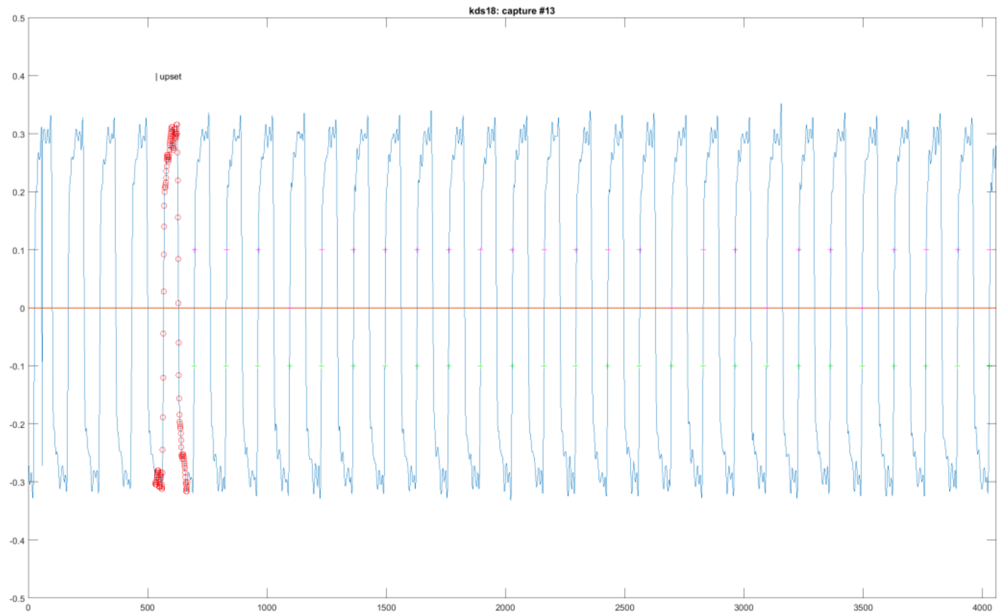
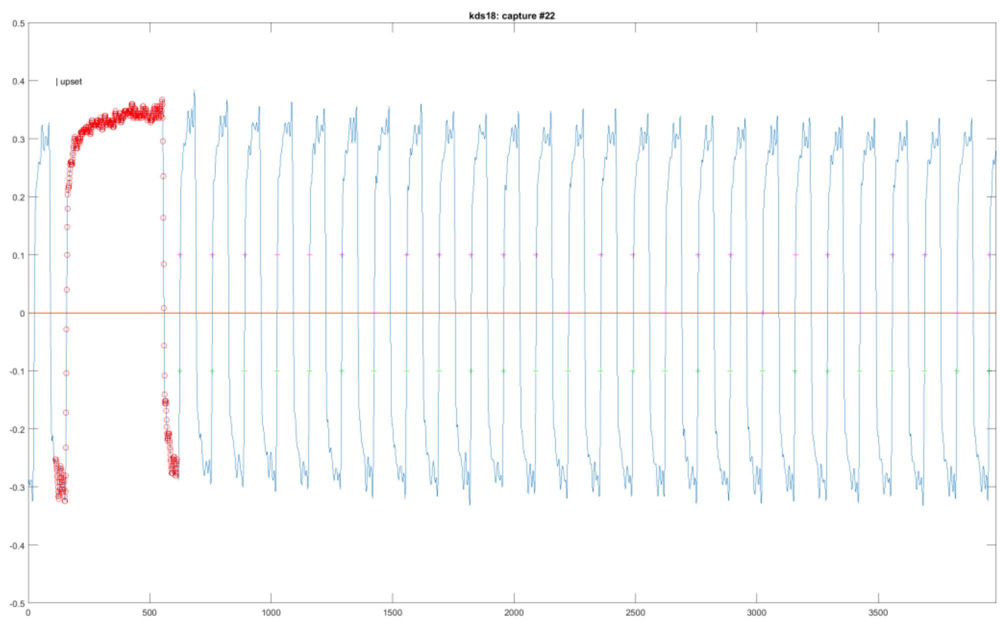


Figure 13.(a) Upset time as they occurred in time and (b) distribution of the upset time for LET=45.25.

The waveform signature seen with an LET=58.78 MeV.cm^2/mg. Figure 14 and **Error! Reference source not found.** shows the analysis done for the LET=58.78.


kds18: capture #13
| upset


kds18: capture #22
| upset

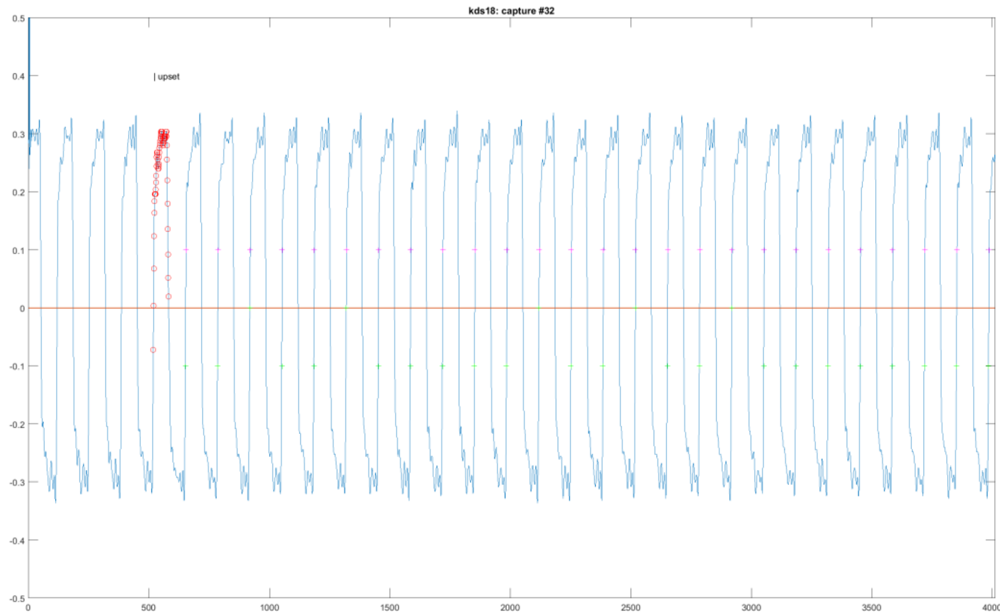


Figure 14.Upset waveform signature at LET=58.78. 3/100 selected to be representative of the upset. (Vertical axis in V and horizontal axis in sample point with a sampling time of 25psec)

(a) (b)

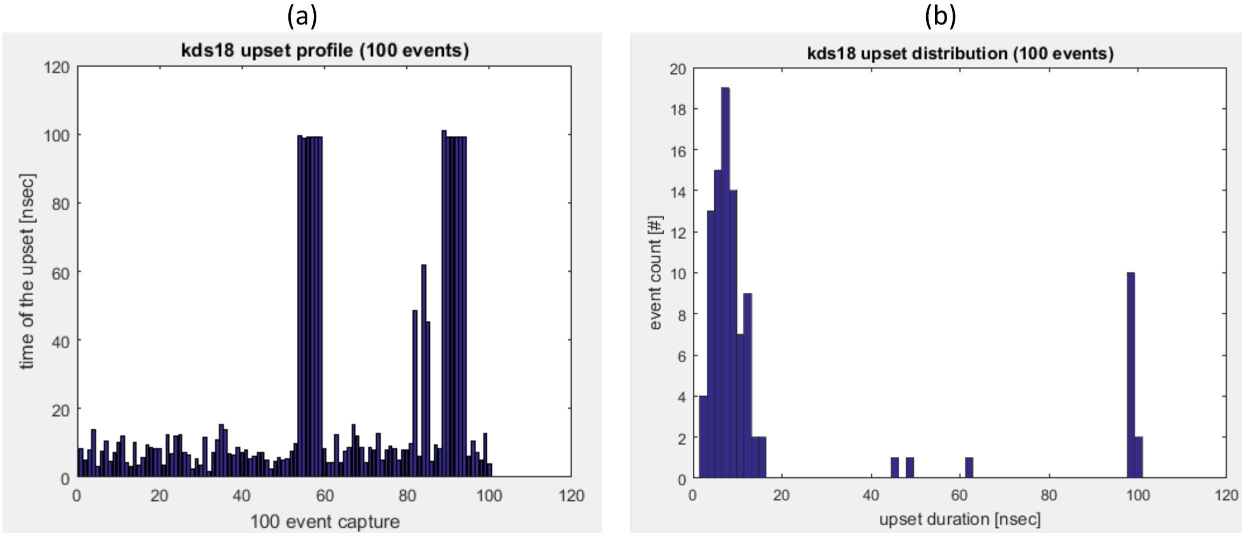


Figure 15.(a) Upset time as they occurred in time and (b) distribution of the upset time for LET=58.78 (KDS18).

7 Conclusion

LMX2615-SP PG1.1 is a space grade device currently in development. It was tested on April 3rd in Berkeley University for single event effect (SEE). We were able to demonstrate that the LMX2615-SP is not having SEL when the LET is less than 121.28 MeV.cm^2/mg.

Single Event Functional Interrupt (SEFI) was observed with Au ions at LET=85.78 MeV.Cm^2/mg while in SPI mode. However, the device will not SEFI with Xe ions at an effective LET=86.19 MeV.Cm^2/mg . We do not have an explanation for this contradictory result.

We obtained a complete data sweep on SEU and were able to measure a figure of merit for the device of 4.95 e-4 event/month while about 90% of the event last less than 15 nsec with LET=58.78 MeV.Cm^2/mg.

8 Acknowledgements

I am grateful to the entire Texas Instruments team who is working tirelessly on this new device. It will offer a space grade, radiation hardened, product with one of the best phase noise performance as a fully integrated wideband synthesizer.

I am also very grateful to ***Kirby Kruckmeyer*** and ***Dennis Wu*** for their instrumental contribution in testing this device at the Berkeley National Laboratory.

9 References

[1] JESD57, "Test procedures for the measurement of single-event effects in semiconductor devices from heavy ion irradiation," Electronic Industries Association, Engineering Department, Arlington VA, 1996.

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