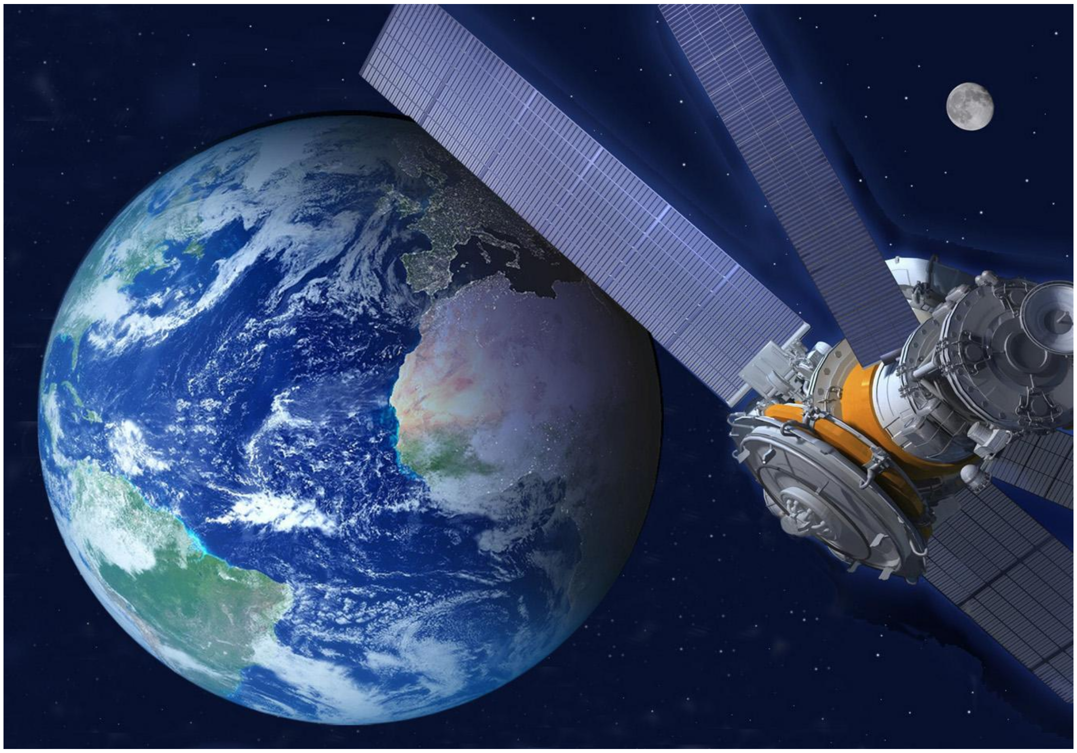
National Semiconductor
Hi-Rel Operations Radiation Engineering/RHA Programs
2900 Semiconductor Drive
Santa Clara, CA 95052

Single Event Effect (SEE) Report

12 b Analog to Digital Converter
8-Channel 50 kS/s to 1 MS/s

ADC128S102WGRQV

(5962R0722601VXA)



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I. Abstract

The ADC128S102WGRQV (SMD number 5962R0722701VZA) was tested for susceptibility to Single Event Latchup (SEL) and Single Event Upsets (SEU). The SEL testing and the majority of SEU testing was performed at the Lawrence Berkeley National Lab 88” Cyclotron. The part was shown to be immune to SEL to a Linear Energy Transfer (LET) of 120 MeV-cm^2/mg, the maximum LET tested.

A limited amount of SEU testing was performed at the Texas A&M Cyclotron Institute. There were some anomalies seen in the data from Texas A&M and there were differences in the SEU cross sections measured between the two facilities. These anomalies and differences are still under investigation. The highest cross section calculated during all of the testing was 4.14 x 10^{-5} cm^2, which equates to 3.34 x 10^{-5} events per month.

II. Product Description

Main Characteristics: The ADC128S102WGRQV is a low-power, eight-channel CMOS 12-bit analog-to-digital converter specified for conversion throughput rates of 50 kS/s to 1 MS/s [1]. The converter is based on a successive-approximation register architecture with an internal track-and-hold circuit. It can be configured to accept up to eight input signals. The output serial data is straight binary and is compatible with several standards, such as SPI™, QSPI™, MICROWIRE™, and many common DSP serial interfaces. The ADC128S102WGRQV may be operated with independent analog and digital supplies. The analog supply (V_A) can range from +2.7 V to +5.25 V, and the digital supply (V_D) can range from +2.7 V to V_A. Normal power consumption using a +3 V or +5 V supply is 2.3 mW and 10.7 mW, respectively. The power-down feature reduces the power consumption to 0.06 µW using a +3 V supply and 0.25 µW using a +5 V supply.

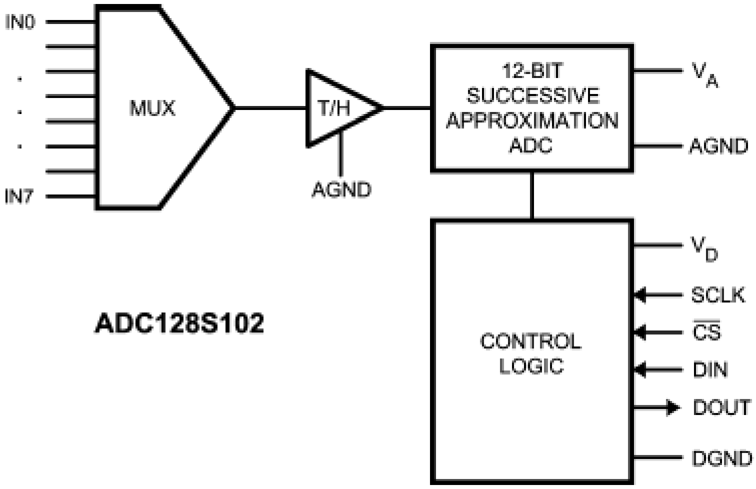


Fig. 1 Block diagram of ADC128S102WGRQV from [1]

Pins: As shown in Fig. 1, analog input data can be read in from one of eight inputs (IN0-IN7) during the first three cycles of SCLK after $\overline{CS}$ is brought low. Converted digital voltages are clocked out serially through DOUT on the falling edges of SCLK. The control register is loaded through DIN on rising edges of SCLK.

Functional Description: The ADC128S102 WGRQV/MLS is a successive-approximation analog-to-digital converter designed around a charge-redistribution digital-to-analog converter. During conversion, the ADC is either in track or hold mode. For the first three cycles after $\overline{CS}$ is brought low, the ADC is in track mode where a switch connects the selected analog input to a sampling capacitor and then switches back to ground to maintain the sampled voltage. At this point, a second switch unbalances the comparator and the control logic instructs the charge-redistribution DAC to add or subtract fixed amounts of charge to or from the sampling capacitor until the comparator is balanced. When the comparator is balanced, the digital word supplied to the DAC is the digital representation of the analog input voltage. The ADC128S102WGRQV is in this state for the last thirteen SCLK cycles after $\overline{\text{CS}}$ is brought low. The digital word that is the output of the device is overwritten for each new serial frame.

III. Test Method

Testing was done according to JESD57 (EIA/JEDEC Standard No. 57), "Test Procedures for the Measurement of Single Event Effects in Semiconductor Devices from Heavy Ion Irradiation" [2].

A. Test Circuit

The devices under test (DUT) were ADC128S102WGRQV die assembled into 16 pin TSSOP packages, that had no lids to expose the die surface to the ion beam. Each unit was soldered to a separate ADC128S102EVAL Board (Fig. 2) [3]. Each DUT was directly powered by a dedicated power supply in order to monitor the current for SEL detection.

The ADC128S102EVAL boards were connected to, and driven by, a WaveVision board and WaveVision4 software [4]. The WaveVision board supplied the input clock and sync signals.

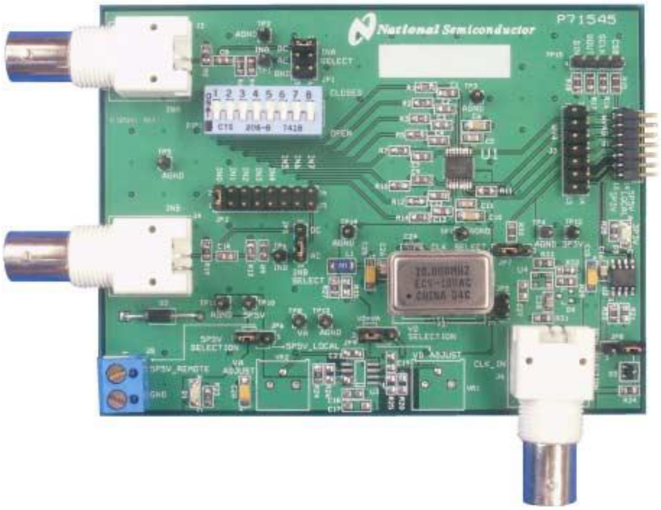


Fig. 2 ADC128S102EVAL board

The conversion rate was 400 ks/S and the digital clock was set to 8 MHz, giving a clock cycle of 125 ns.

At Berkeley, IN1 (channel 2) was used to supply the input voltage, while at Texas A&M IN0 (channel 1) was used.

B. Test Setup

Berkeley

Fig. 3 shows the setup used for the SEL and SEU testing at Berkeley. Equipment was located in the control room and the test chamber. Berkeley tests in vacuum, so there is a vacuum chamber within the test chamber. Testing was performed with the DUT in the dark.

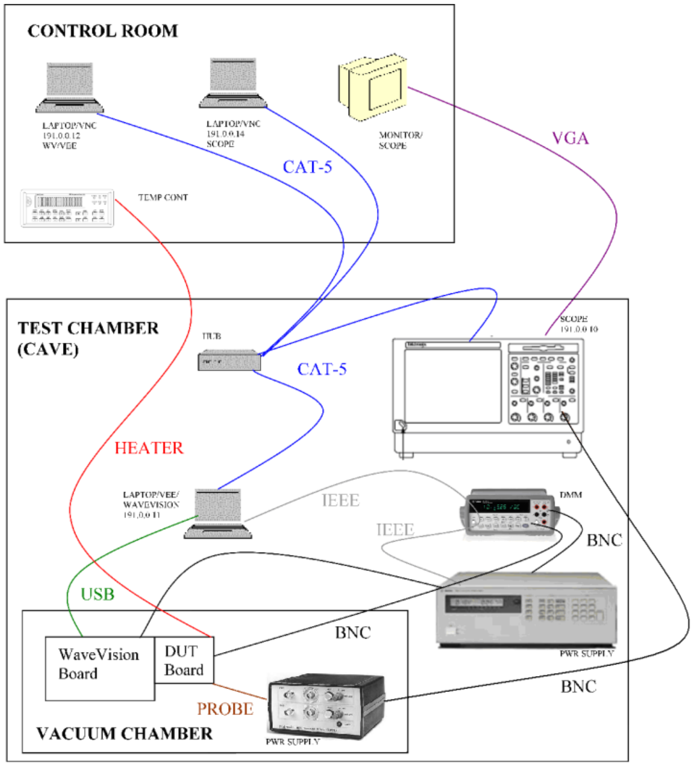


Fig. 3 Equipment setup for SEL and SET testing at Berkeley

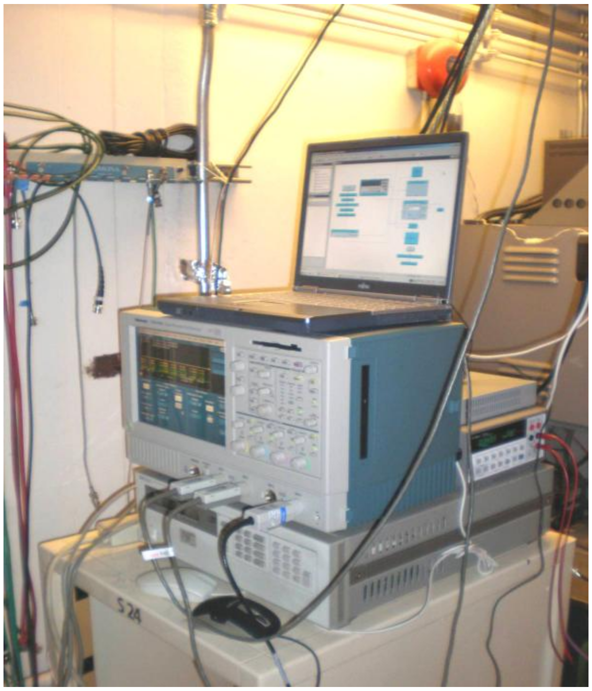


Fig. 4 Measurement setup in the test chamber

The power supply in the test chamber but outside the vacuum chamber that powered the WaveVision board and the ADC128S102WGRQV was the Agilent 6626A. The input current was monitored through the Agilent 34401A and both instruments were interfaced to the monitoring laptop computer using an IEEE 488 digital communications bus (Fig. 4). A hub connected the monitoring laptop to one of two controlling laptops located in the control room (Fig. 5). One control laptop could manage the power up and power down sequences remotely by using Agilent VEE Pro 8.0, reducing the human interaction required while the device was setup in the test chamber.

Supply voltage level to the DUT was verified by measuring voltage at the ADC128S102EVAL V_A input before the vacuum chamber was sealed.

The other laptop in the control room was connected to the Tektronix 7404B oscilloscope in the test chamber, through the hub also using an IEEE 488 digital communications bus. The 7404B was connected to the probe power supply, a Tektronix 1103, inside the vacuum chamber, which was in turn connected to the output of the DUT. The output of the scope was viewable on a monitor in the control room, connected to the oscilloscope through a VGA cable. Real VNC software was used on both control laptops to control the oscilloscope and VEE Pro and WaveVision programs.

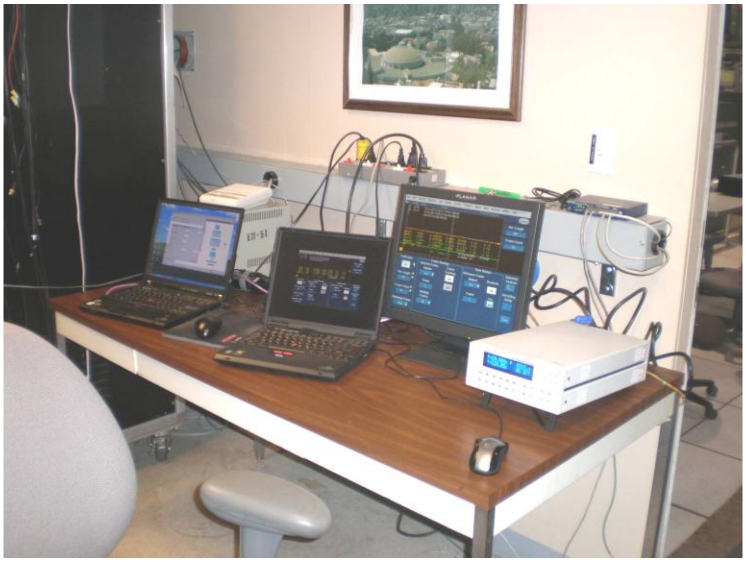


Fig. 5 Setup in the control room

Test Setup: Texas A&M

At The Radiation Effects Facility at The Cyclotron Institute testing was done in air, as opposed to vacuum. There was a light on during testing. The tests were observed and controlled with computers in the room overlooking the test chamber (Fig. 6). In the test chamber, the DUT was placed in a vice in front of the beam port (Fig. 7). The power supply for the WaveVision board and the EVAL board was an Instek PC-3030D dual output, and the supply for the input voltage was an HP 6114A. The oscilloscope was a Tektronix 7404B and the multi meter used to monitor the input current was an Agilent 34401A.

Fig. 6 Control room above the test chamber

C. SEL

Any sudden operating current increase of more than 10 µA was considered a latchup condition. In addition to manual monitoring, a software routine was written in VEE Pro 8.0 to automatically power down the device in case of Single Event Latchup (increase in operating current above 3 mA).

Fig. 7 Beam port and exposure table

At Berkeley, the DUTs were tested at elevated temperature around 125°C. A resistive heater was attached to the backside of the ADC128S102EVAL board, directly under the DUT. A thermister was epoxied close to the DUT to monitor the board temperature. The thermister and heaters were connected to a Lakeshore temperature controller. Supply current was monitored during SEU testing at room temperature at both Berkeley and Texas A&M.

D. SEU

Devices tested at Lawrence Berkeley National Laboratory were irradiated with a variety of ions at a supply voltage of either 5.25 V or 2.7 V, and with an output of full scale or zero scale. The input voltage was adjusted until the desired digital output was achieved (either full or zero scale). At Berkeley the DUT is in vacuum, requiring the longer cables and the use of vacuum feed throughs, resulting in higher background noise. For this reason the input was taken slightly beyond the part rails to achieve stable zero or full scale outputs. When the supply voltage was 5.25 V, it was necessary to set the input voltage to 5.4 V to get a stable full scale output. To get a stable zero scale output, it was necessary to set the input to -0.2 V. Since testing at Texas A&M was done in room air, the interface to the part was more direct and there was less noise in the system. To get a zero scale output, the input voltage supply was turned off. To get the full scale output, the input voltage was set closer to the supply voltage (5.30 V for the 5.25 V supply voltage). However, due to limited test time at Texas A&M, it was not possible to monitor the stability of the output over a long period of time.

Devices tested at Texas A&M Cyclotron Institute were only irradiated with Xenon (varying the incident angle to vary the effective LET). Each run lasted until the oscilloscope was triggered by an error 100 times or the fluence reached 10^7 ions/cm^2. DUT 1 was tested at Berkeley, DUT 3 was tested at both facilities, and DUT 4 was tested at Texas A&M. The details of the various setups are shown in Table 1.

Table 1
SEU testing conditions for all DUTs

Device	Supply voltage (V)	Output scale (%)	Beam energy (MeV/nucleon)	LETs (MeV/(mg/cm^2))
DUT 1	5.25	100	4.5	121.76, 99.74, 87.15, 77.52, 68.84, 39.25, 29.33, 14.32, 5.77
	5.25	0	4.5	99.74, 87.15, 77.52, 68.84, 39.25, 29.33
	2.7	100	4.5	99.74, 87.15, 77.52, 68.84, 39.25, 29.33, 14.32, 5.77
DUT 3	5.25	100	4.5	99.74, 87.15, 77.52, 68.84, 39.25, 29.33, 14.32
	5.25	0	4.5	99.74, 87.15, 77.52, 39.25
	5.25	100	24.8	58.7
	5.25	0	24.8	58.7, 41.5
	3	100	24.8	41.5
DUT 4	5.25	100	24.8	58.7, 41.5
	5.25	0	24.8	58.7, 41.5

In normal operating conditions at Berkeley, the background noise due to the data acquisition system of the oscilloscope (Tektronix TDS7404B) and the long BNC cables (connecting the scope to the DUT in the vacuum chamber), required that the oscilloscope be set to detect errors greater than 1 least significant bit (LSB). At Texas A&M the oscilloscope was set to detect errors of 1 LSB or higher.

E. Test Sequence

Berkeley – December 11, 2007

First, SEU testing was performed on DUT 1 at room temperature, using full scale outputs with supply voltages of 5.25 V and 2.7 V. Next, DUT 1 was heated to125°C. SEL testing was done using a Bi ion beam with the board oriented to the beam at 0° and 35°. After DUT 1 settled back to room temperature, testing was done with a supply voltage of 5.25 V and zero scale output. Finally, SEU testing on DUT 3 at room temperature was done with a supply voltage of 5.25 at zero and full scale outputs. Then, DUT 3 was heated to roughly 125°C and SEL testing was done using a Bi ion beam with the board oriented to the beam at 0° and 35°.

Berkeley – February 12, 2008

DUT 4 was heated to 125°C and SEL testing was done using a Bi ion beam with the board oriented at 35°.

Texas A&M – June 20, 2008

First, SEU testing was performed on DUT 3 with a supply voltage of 5.25 V with full and zero scale outputs and with a supply voltage of 3 V with a full scale output. Then, SEU testing was done on DUT 4 with a supply voltage of 5.25 V at full and zero scale outputs.

F. Test Equipment

Berkeley

1. ADC128S102EVAL Boards
2. WaveVision board.
3. Power supply Agilent 6626A
4. Power supply Tektronix 1103
5. Oscilloscope Tektronix TDS 7404B
6. Lakeshore Temperature Controller, Model 332
7. Laptop Computer with WaveVision 4 Software
8. Digital Multi Meter Agilent 34401A

Texas A&M

1. ADC128S102EVAL Boards
2. WaveVision board.
3. Power supply HP 6114A
4. Power supply Instek Dual Output
5. Power supply Tektronix 1103

6. Oscilloscope Tektronix TDS 7404B
7. Lakeshore Temperature Controller, Model 332
8. Laptop Computer with WaveVision 4 Software
9. Digital Multi Meter Agilent 34401A

G. Test Facility and Ion Beams

Testing for DUT 1 and part of DUTs 3 and 4 was done using the 88" cyclotron at the Berkeley Accelerated Space Effect facility at the Lawrence Berkeley National Laboratory.

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720
http://user88.lbl.gov/

The 4.5 MeV/nucleon beam used the following ions in testing:
Ne, Ar, Cu, Kr, Xe, Tb, Ta and Bi

Testing for DUT 4 and part of DUT 3 was done using the K500 cyclotron at the Radiation Effects Facility at the Cyclotron Institute.

Cyclotron Institute
Texas A&M University
MS #3366
College Station, TX 77843

The 24.8 MeV/nucleon beam used Xe in testing. There was a lengthy waiting period to change ions and time was limited so no other ions were used.

The energies and penetration depths are shown in Appendices A and B.

IV. Test Results

A. SEL

No incidences of SEL or any hard errors were detected. No surges in supply current were seen and the supply current variation was less than 5 μA during every ion run. The DUT continued to operate properly after every ion run.

B. SEU

DUT 1 – Berkeley, 5.25 V Supply

Ion	LET_{eff} (MeV/(mg/cm^2))	Full Scale			Zero Scale		
		Errors	Fluence (ions/cm^2)	Cross section (cm^2)	Errors	Fluence (ions/cm^2)	Cross section (cm^2)
Bi (35°)	121.76	100	7.40E+06	1.35E-05			
Bi	99.74	200	1.86E+07	1.07E-05	21	1.00E+07	2.10E-06
Ta	87.15	25	2.00E+06	1.25E-05	13	1.00E+07	1.30E-06
Tb	77.52	45	1.00E+07	4.50E-06	13	1.00E+07	1.30E-06
Xe	68.84	40	1.00E+07	4.00E-06	6	1.00E+07	6.00E-07
Kr	39.25	18	1.00E+07	1.80E-06	2	1.00E+07	2.00E-07
Cu	29.33	6	1.00E+07	6.00E-07	2	5.01E+07	3.99E-08
Ar	14.32	17	2.00E+07	8.50E-07			
Ne	5.77	5	8.00E+07	6.25E-08			

DUT 1 Berkeley, 2.7 V Supply

Ion	LET_{eff} (MeV/(mg/cm^2))	Full Scale		
		Errors	Fluence (ions/cm^2)	Cross section (cm^2)
Bi	99.74	77	1.00E+07	7.70E-06
Ta	87.15	53	1.00E+07	5.30E-06
Tb	77.52	28	1.00E+07	2.80E-06
Xe	68.84	30	1.00E+07	3.00E-06
Kr	39.25	15	2.00E+07	7.50E-07
Cu	29.33	3	1.00E+07	3.00E-07
Ar	14.32	3	1.00E+07	3.00E-07
Ne	5.77	0	5.00E+07	0.00E+00

DUT 3 – Berkeley, 5.25 V Supply

Ion	LET_{eff} (MeV/(mg/cm^2))	Full Scale			Zero Scale		
		Errors	Fluence (ions/cm^2)	Cross section (cm^2)	Errors	Fluence (ions/cm^2)	Cross section (cm^2)
Bi	99.74	52	1.00E+07	5.20E-06	17	1.00E+07	1.70E-06
Ta	87.15	55	1.00E+07	5.50E-06	18	1.00E+07	1.80E-06
Tb	77.52	54	1.00E+07	5.40E-06	9	1.00E+07	9.00E-07
Xe	68.84	26	1.00E+07	2.60E-06			
Kr	39.25	22	2.00E+07	1.10E-06	7	2.00E+07	3.50E-07
Cu	29.33	5	1.00E+07	5.00E-07			
Ar	14.32	4	4.00E+07	1.00E-07			

DUT 3 – Texas A&M, 5.25 V Supply

Ion	LET_{eff} (MeV/(mg/cm^2))	Full Scale			Zero Scale		
		Errors	Fluence (ions/cm^2)	Cross section (cm^2)	Errors	Fluence (ions/cm^2)	Cross section (cm^2)
Xe(-45°)	58.7	400	9.66E+06	4.14E-05	100	1.40E+07	7.14E-06
Xe	41.5	400	1.18E+7	3.40E-05	100	2.00E+07	5.00E-06

DUT 3 – Texas A&M, 3.0 V Supply

Ion	LET_{eff} (MeV/(mg/cm^2))	Full Scale		
		Errors	Fluence (ions/cm^2)	Cross section (cm^2)
Xe	41.5	400	2.08E+07	1.92E-05

DUT 4 – Texas A&M, 5.25 V Supply

Ion	LET_{eff} (MeV/(mg/cm^2))	Full Scale			Zero Scale		
		Errors	Fluence (ions/cm^2)	Cross section (cm^2)	Errors	Fluence (ions/cm^2)	Cross section (cm^2)
Xe(-45°)	58.7	400	1.31E+07	3.04E-05	120	1.48E+07	8.13E-06
Xe	41.5	420	1.65E+07	2.55E-05	100	1.43E+07	7.02E-06

V. Analysis of SEUs

Key Observations

The SEU LET threshold was found to be between 5.77 and 14.32 MeV/(mg/cm^2) for a supply voltage of 2.7 V and a full scale output at a beam energy of 4.5 MeV/nucleon.

DUT 3 appeared to reach a saturated cross section of roughly 5.5 x 10^{-6} cm^2 with a supply voltage of 5.25 V and a full scale output.

The worst case conditions for Single Event Upset cross sections were a supply voltage of 5.25 V and a full scale output. Under these conditions, the largest cross section was 4.14 x 10^{-5} cm^2.

The number of events per month calculated for the worst case conditions was 3.34 x 10$^{-5,}$ the highest number for any set of conditions.

Differences in results were seen in the testing at Berkeley and Texas A&M. The cross sections for the Texas A&M testing were roughly an order of magnitude higher than those for the testing at Berkeley at comparable LETs. Events lasting more than one sample cycle were seen at Texas A&M, while at Berkeley, all events were just one sample long.

A. Statistical Analysis

The Weibull distribution [5] was used to statistically characterize the failure behavior of the device. Furthermore, a figure of merit equation [6] was used to predict the monthly upset rate of the DAC.

Weibull Distribution

The integral form of the distribution that describes the event cross-sections as a function of LET is:

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

$$F(L) = 0; L < L_0$$

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

For the ease of calculation, L_0 was set to 0 and W was set to 100. The values of A and s were adjusted to fit the actual data.

Figure of Merit

The following figure of merit was used to characterize the monthly number of errors in a geosynchronous orbit from the ADC output:

$$\mathrm{FOM} = 30 \times 200 \times \frac{\sigma_{\mathrm{limit}}}{L_{0.25}^{2}}$$

where, $\boldsymbol{\sigma_{\mathrm{lim}}}$ is the limiting cross-section
$\mathbf{L_{0.25}}$ is the LET at 25% of the limiting cross-section

The multiplication by 30 in the FOM was used to get the monthly number of events.

The Weibull fits performed on data from Berkeley for DUT 1 and DUT 3 are shown in Figs. 8 and 9 respectively.

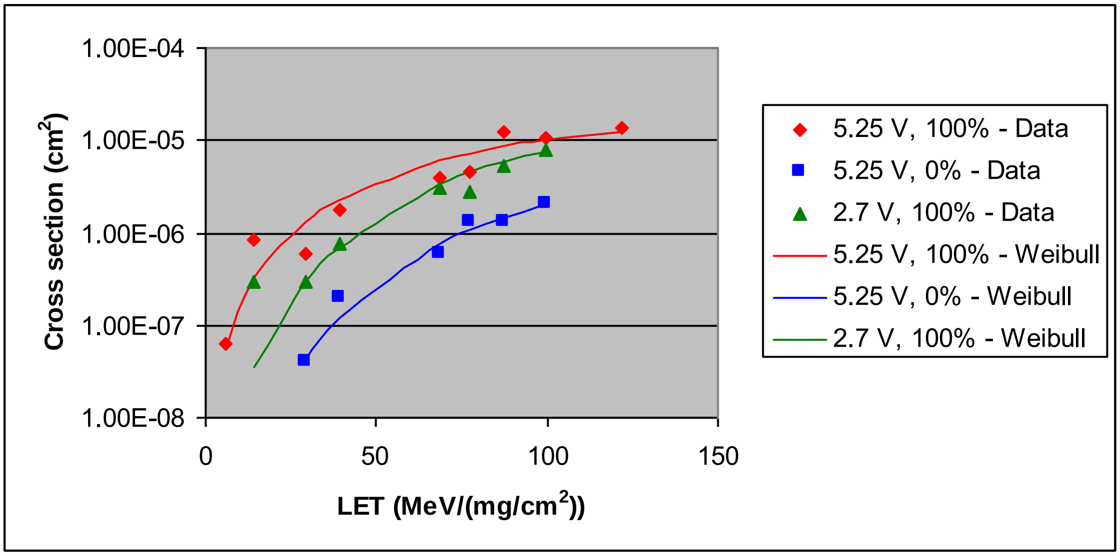


Fig. 8 Cross section vs. LET data and Weibull distribution for DUT 1 tests at Berkeley

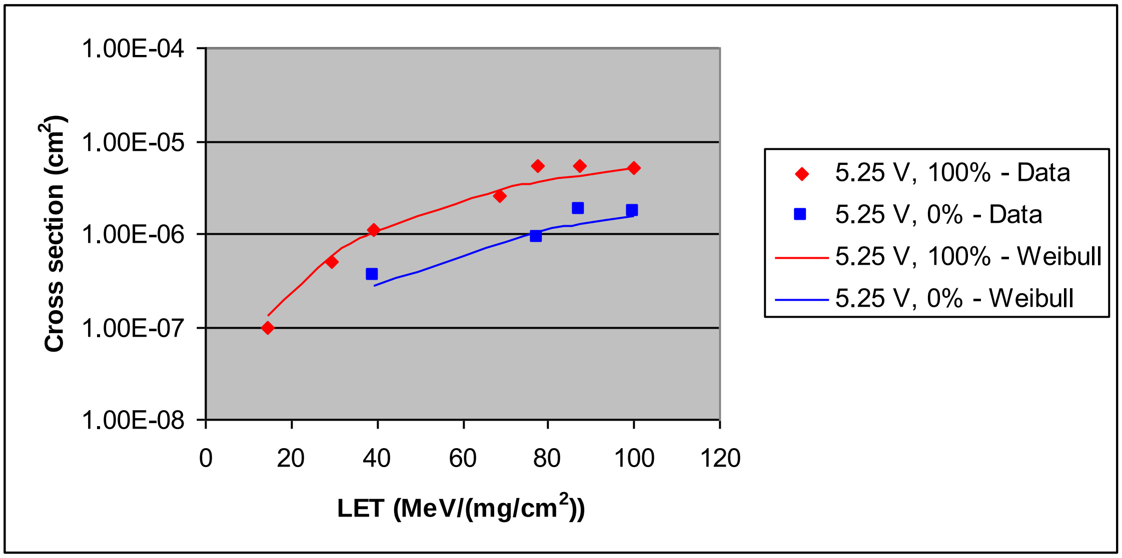


Fig. 9 Cross section vs. LET data and Weibull distribution for DUT 3 tests at Berkeley

The parameters for the Weibull distributions are listed in Table 2.

Table 2
Weibull parameters used for tests on DUTs 1 and 3 at Berkeley

Device	Supply Voltage (V)	Output Scale (%)	A	W	L_0	s
DUT 1	5.25	100	1.60E-05	100	0	2
	5.25	0	3.20E-06	100	0	3.5
	2.7	100	1.20E-05	100	0	3
DUT 3	5.25	100	8.00E-06	100	0	2.1
	5.25	0	2.50E-06	100	0	2.3

From the Weibull fits a figure of merit was calculated that estimated the monthly number of events. The results are listed in Table 3.

Table 3
Figures of merit and monthly events for testing on DUT 1 and 3 done at Berkeley

Device	Supply Voltage (V)	Output Scale (%)	FOM (events/month)
DUT 1	5.25	100	3.34E-05
	5.25	0	3.91E-06
	2.7	100	1.65E-05
DUT 3	5.25	100	1.57E-05
	5.25	0	4.43E-06

B. Parameter Analysis

Supply Voltage

The cross sections recorded with a supply voltage of 5.25 V ranged from 1.4 to 2.8 and averaged 2 times larger than those recorded for lower supply voltages. The cross sections recorded at Berkeley with a supply voltage of 5.25 V were on average 2 times larger than those recorded at 2.7 V. Fig. 10 plots data for DUT 1 at both voltages. Note that at the lowest LET of 5.77 MeV/(mg/cm^2) , the 2.7 V cross section is actually zero, but is not plotted on the graph because the y-axis is on a logarithmic scale. The cross section recorded at Texas A&M with a supply voltage of 5.25 V was 1.8 times larger than that recorded at 3 V. Fig. 11 plots DUT 3 at both of these voltages.

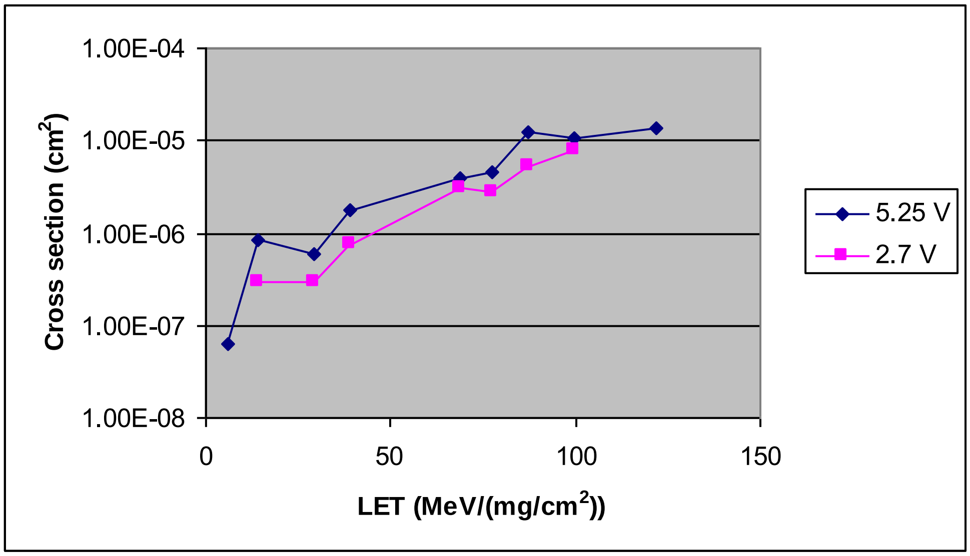


Fig. 10 Cross section vs. LET for DUT 1 at supply voltages of 5.25 V and 2.7 V, each at full scale output

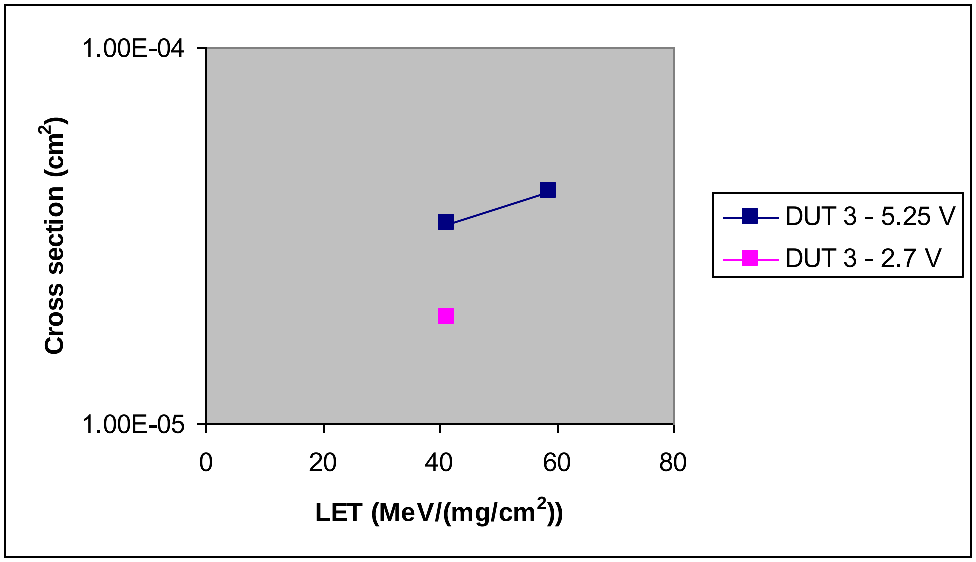


Fig. 11 Cross section vs. LET for DUT 3 at supply voltages of 5.25 V and 3 V, each at full scale output

Output Scale

On average, the cross sections recorded at full scale output were 6 times greater (with values ranging from 3 to 15 times greater) than those recorded for zero scale output. At Berkeley, cross sections for DUT 1 at full scale averaged 8.2 times larger than those at zero scale. At Berkeley, cross sections for DUT 3 at full scale averaged 3.8 times larger than those at zero scale. Both were tested at a supply voltage of 5.25 V. These results are plotted in Fig. 12. At Texas A&M, cross sections for DUT 3 at full scale were on average 6.3 times larger than those at zero scale. At Texas A&M cross sections for DUT 4 were on average 3.7 times larger than those at zero scale. These results are plotted in Fig. 13.

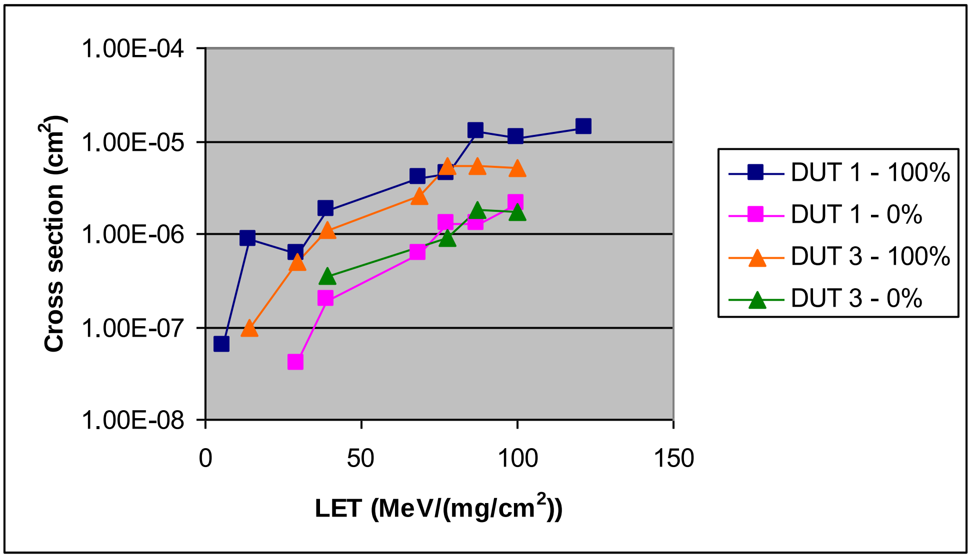


Fig. 12 Cross section vs. LET for DUT 1 and 3 with a supply voltage of 5.25 V at full and zero scale outputs. DUT 1 is plotted with squares and DUT 3 is plotted with triangles.

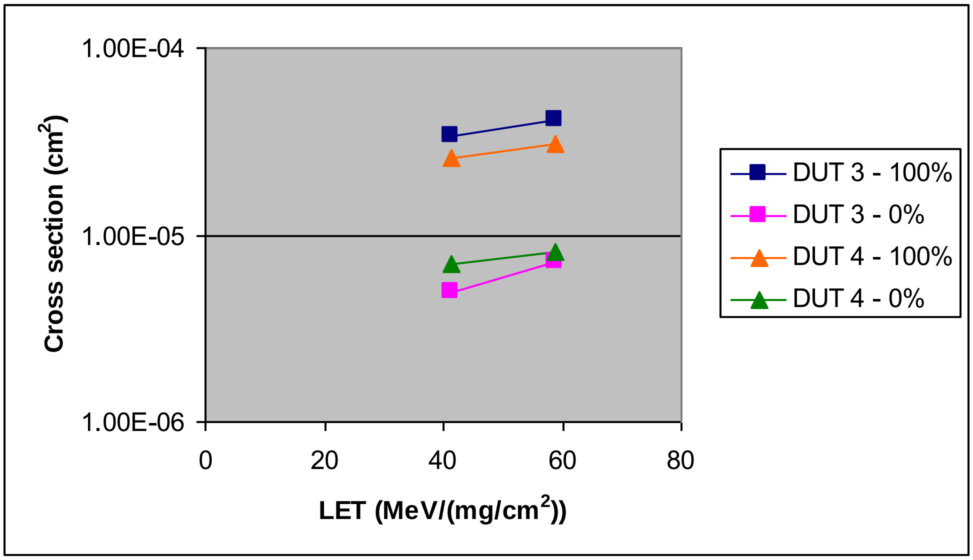


Fig. 13 Cross section vs. LET for DUT 3 and 4 with a supply voltage of 5.25 V at full and zero scale outputs. DUT 3 is plotted with squares and DUT 4 is plotted with triangles.

C. Part to Part Variation

Berkeley Tests

The cross sections from DUT 1 at Berkeley ranged from 0.6 to 8.5 and averaged 2 times larger than those from DUT 3. At full scale the cross sections of DUT 1 averaged 2.58 times larger than those of DUT 3. At zero scale the cross sections of DUT 1 were on average equal to those of DUT 3. At high LETs, DUT 1 had significantly higher cross sections while DUT 3 looks as though it has reached a saturated cross section of roughly 5.5 x 10^{-6} cm^2. All of this can be seen graphically in Fig. 12.

Texas A&M

Testing on DUTs 3 and 4 at Texas A&M was only done for 2 LETs at a supply voltage of 5.25 V (Fig. 13). At full scale the cross sections for DUT 3 were on average 1.4 times larger than those of DUT 4. At zero scale the cross sections for DUT 3 were on average 0.8 times larger than those of DUT 4.

D. Testing Facility Differences

DUT 3 was the only DUT to undergo SEU testing at both facilities. In order to make the data sets comparable, all 1 LSB errors were omitted from the Texas A&M tests since data from Berkeley did not include these. On average, the cross sections for DUT 3 from Texas A&M were 11.8 times larger than those for DUT 3 at Berkeley. At full scale the cross sections for DUT 3 at Texas A&M were 10 times larger than those at Berkeley. At zero scale the cross sections for DUT 3 at Texas A&M were on average 12.8 times larger than those at Berkeley. Tests performed at Berkeley used a beam energy of 4.5 MeV/nucleon in vacuum, while those at Texas A&M used a beam energy of 24.8 MeV/nucleon in air. The results are plotted in Fig. 14.

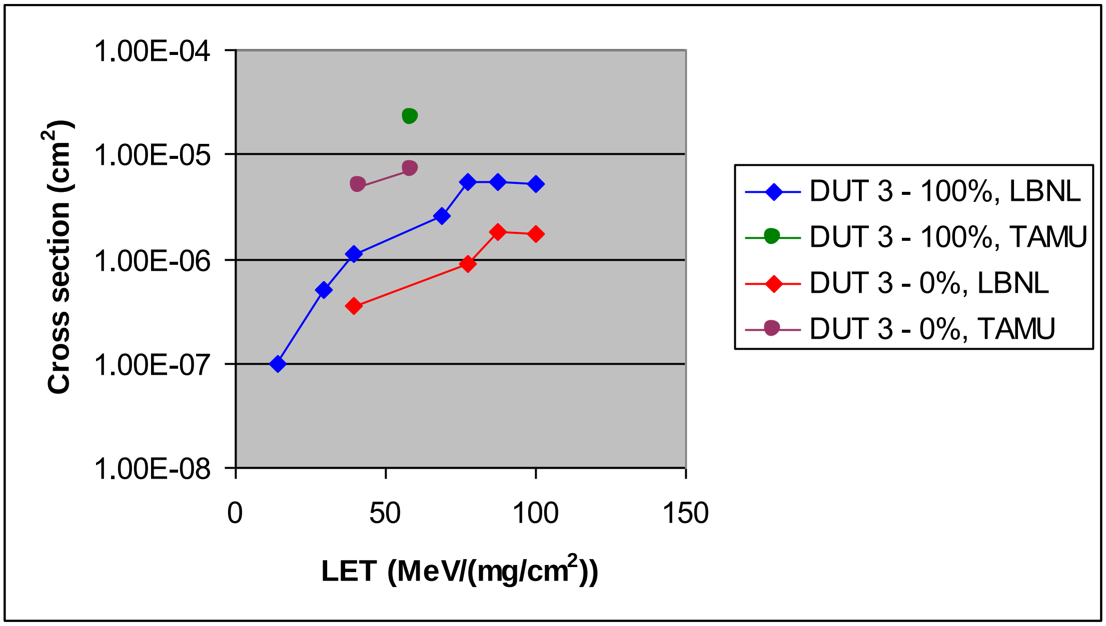


Fig. 14 Cross section vs. LET for DUT 3 with a supply voltage of 5.25 V at full and zero scale output. Berkeley data is plotted with diamonds and Texas A&M data is plotted with circles.

E. SEU Signatures

Full Scale

An example of a typical full scale error can be seen in Fig. 18. For all testing conditions, the least significant bits were more prone to upset. It was uncommon to see any bit above 6 (numbering bits 1-12 with 1 being the least significant and 12 being the most significant) upset and very rare to see any bit above 9 upset. A breakdown of the errors by LSB is shown in Fig. 15. Since this is a 12 bit output, the highest error magnitude is $2^{12} - 1$, or 4095 LSB.

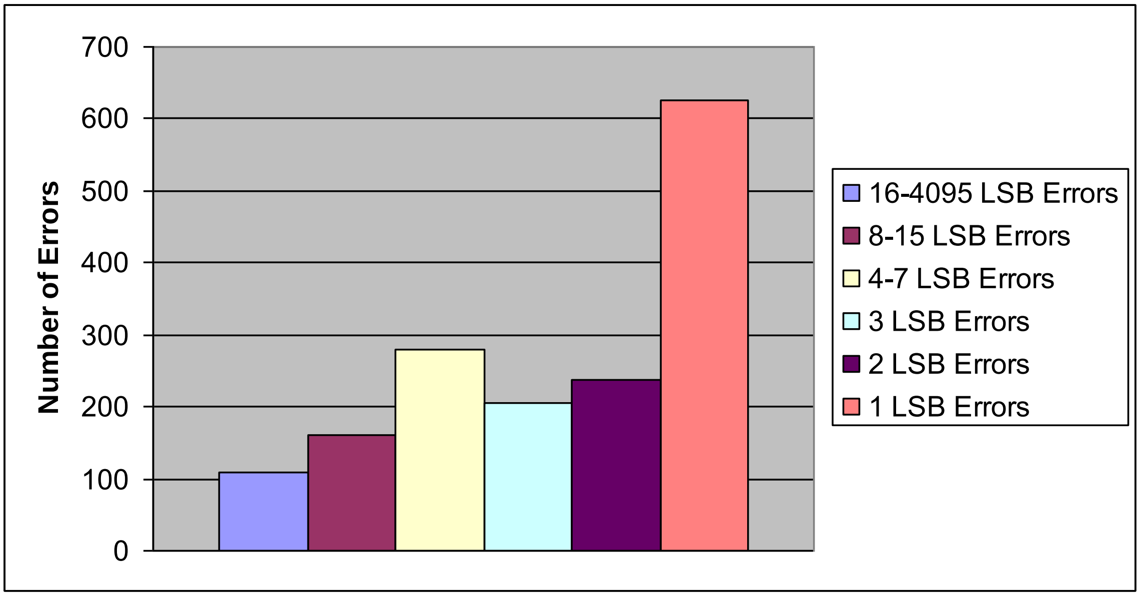


Fig. 15 Number of errors recorded during SEU testing at Texas A&M for DUTs 3 and 4 at full scale output divided into columns by LSB error magnitude.

There were 1620 total errors. Of these, 626, or 39% were 1 LSB errors and only 110, or 7% had an error magnitude between 16 and 4095 LSBs. This chart only refers to tests performed at Texas A&M because tests at Berkeley could not identify 1 LSB errors. However, the errors seen at Berkeley still favored the least significant bits.

Cross sections with and without 1 LSB errors are listed in Tables 4 and 5 to show the effect they have on the cross sections of tests from Texas A&M. There is no entry for DUT 3 at 5.25 V and an LET of 41.5 MeV/(mg/cm^2) because the waveform data was not available and the LSB magnitude of the errors could not be counted.

Table 4
Cross sections for DUT 3 using a 24.8 MeV/nucleon beam with and without 1 LSB errors

Supply Voltage (V)	Output Scale (%)	Species	LET (MeV/(mg/cm^2))	Number of Errors	Fluence (ions/cm^2)	Cross section (cm^2)	Number of 1 LSB Errors	New cross section (cm^2)
5.25	100	Xe (-45°)	58.7	400	9.66E+06	4.14E-05	185	2.23E-05
3	100	Xe	41.5	400	2.08E+07	1.92E-05	129	1.30E-05

Table 5
Cross sections for DUT 4 with and without 1 LSB errors

Supply Voltage (V)	Output Scale (%)	Species	LET (MeV/(mg/cm^2))	Number of Errors	Fluence (ions/cm^2)	Cross section (cm^2)	Number of 1 LSB Errors	New cross section (cm^2)
5.25	100	Xe (-45°)	58.7	400	1.31E+07	3.04E-05	144	1.95E-05
5.25	100	Xe	41.5	420	1.65E+07	2.55E-05	168	1.53E-05

All errors went to the rail, no errors peaked at voltages between V_A and 0 V.

Zero Scale

An example of a common zero scale error is shown in Fig. 16. The exact bits being upset could not be identified at zero scale output, so an analysis on LSBs cannot be performed. Instead, the number of bits that were upset for each error at Texas A&M were counted and the results are shown in Fig. 17.

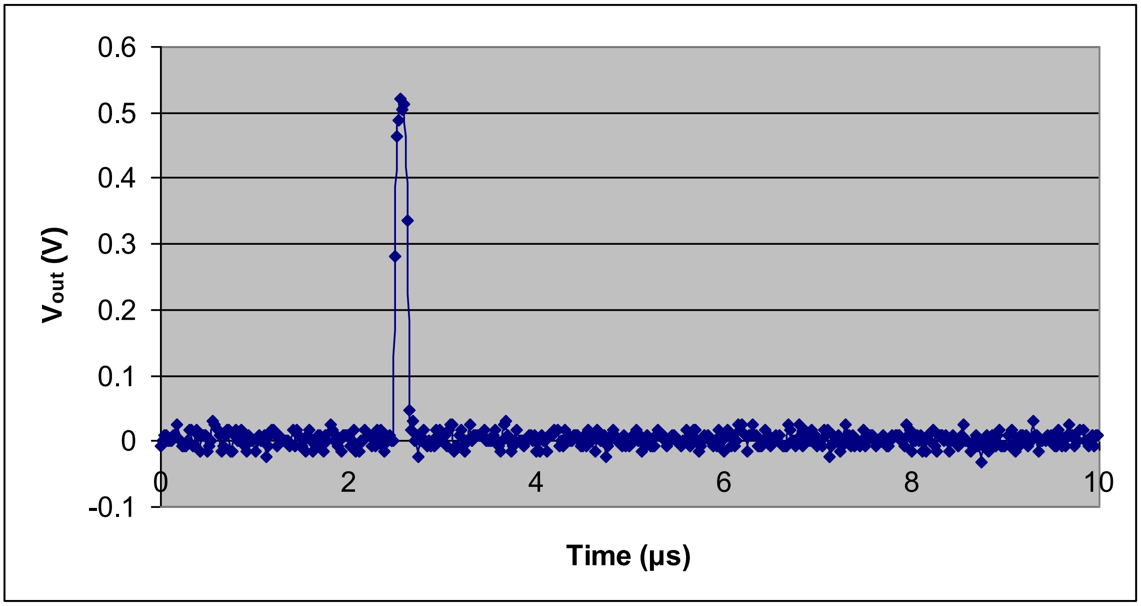


Fig. 16 Output of DUT 3 when irradiated with a 24.8 MeV/nucleon beam composed of Xe with a supply voltage of 5.25 V and a full scale output. The output has 12 bits read out from the ADC in order from most significant to least significant, which takes 1.5 µs, and then 1 µs of zeros, and then the process repeats. All 12 bits of every output are supposed to be low so the output should be constantly zero. The error in this window occurs at 2.5 µs and represents 1 bit flipped.

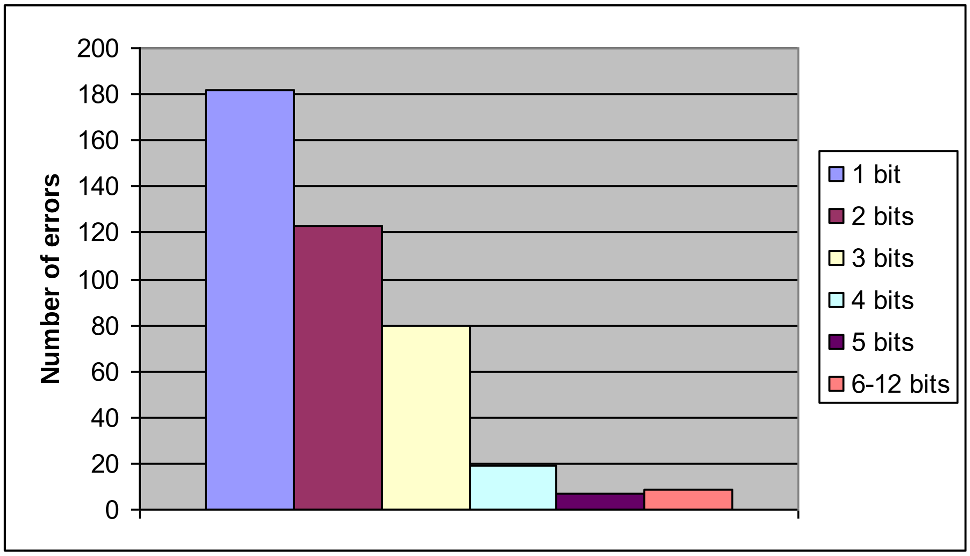


Fig. 17 Number of errors recorded during SEU testing at Texas A&M for DUTs 3 and 4 at zero scale output divided into columns by the number of bits upset.

There were 420 total errors. Of these, 182, or 43% were 1 bit errors, while 9, or 2% were 6 to 12 bit errors. There was one 12 bit error. The data is skewed towards upsets with small amounts of bits. All errors went to V_A, no voltages peaked between V_A and 0 V.

F. Multiple Cycle Errors

Errors produced at Berkeley lasted for one sample cycle while errors produced at Texas A&M would often last for multiple cycles. An example of a typical error from Berkeley is shown in Fig. 18. An example of a multiple cycle error from Texas A&M is shown in Fig. 19. Note also that the bits that are upset are not necessarily the same from cycle to cycle.

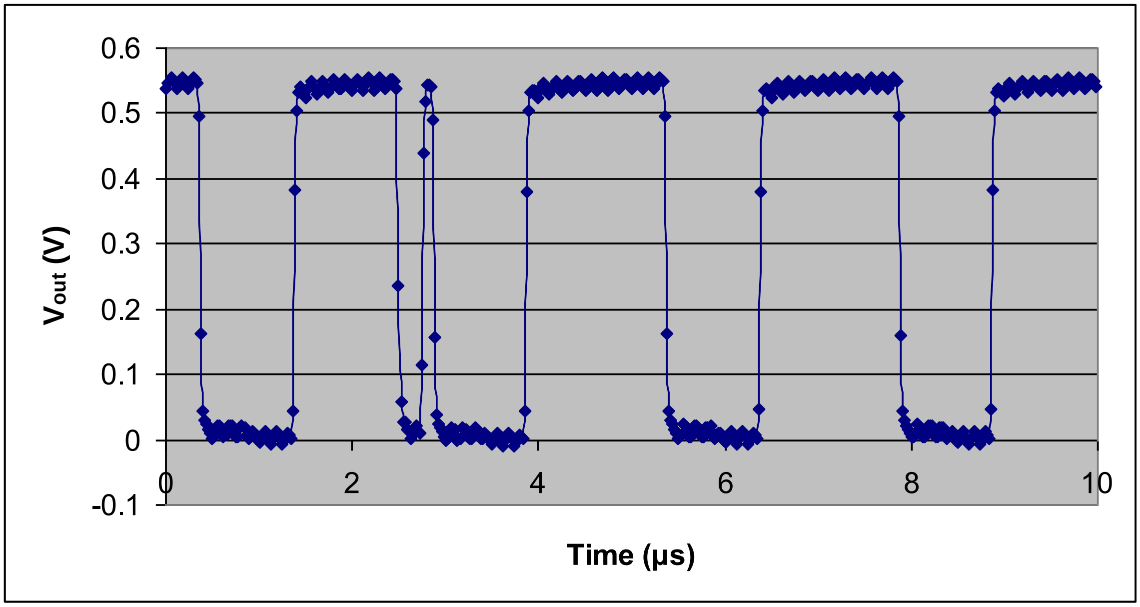


Fig. 18 Output of DUT 3 when irradiated with a 4.5 MeV/nucleon beam composed of Bi with a supply voltage of 5.25 V and a full scale output. The output has 12 bits read out from the ADC in order from most significant to least significant, which takes 1.5 µs, and then 1 µs of zeros, and then the process repeats. All 12 bits of every output are supposed to be high and the 12 bit output centered around 2 µs has the second and third least significant bit at zero.

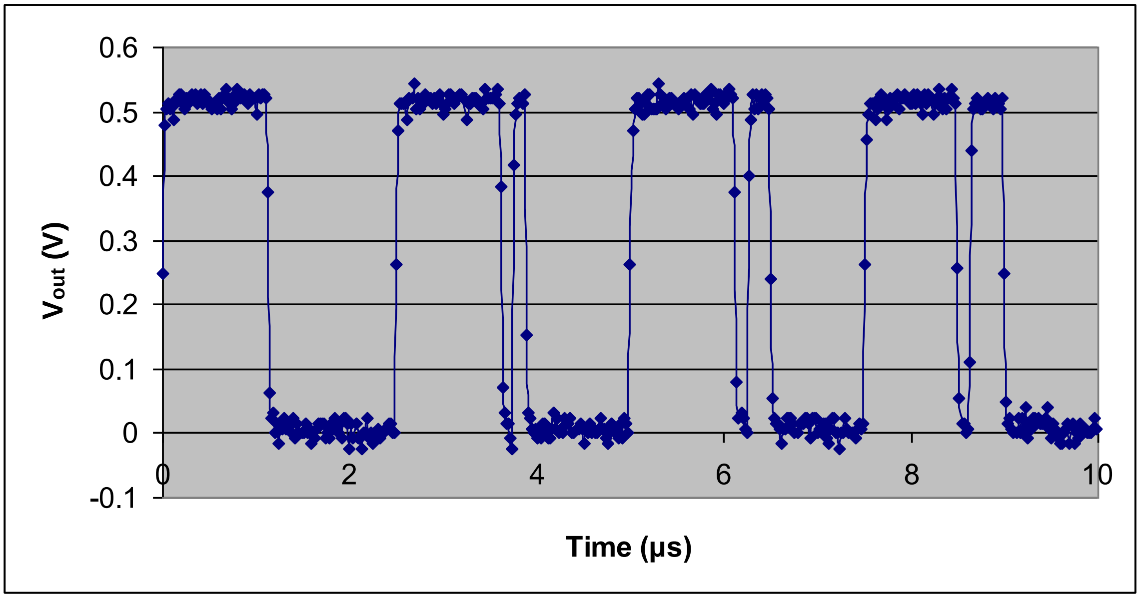


Fig. 19 Output of DUT 4 when irradiated with a 24.8 MeV/nucleon beam composed of Xe and angled at -45° with a supply voltage of 5.25 V and a full scale output. The output has 12 bits read out from the ADC in order from most significant to least significant, which takes 1.5 µs, and then 1 µs of zeros, and then the process repeats. All 12 bits of every output are supposed to be high. The first 12 bit output cycle has its three least significant bits at zero, the second cycle has its first and third least significant bit at zero, the third cycle has its third most significant bit at zero, and the fourth cycle has its fourth least significant bit at zero.

Out of the 2440 errors recorded over all runs at Texas A&M, 2040 had scope data to analyze (one run with 400 errors did not save the error windows). 222 windows out of the 2040 (11%) showed errors in multiple cycles. Tests at zero scale output seemed more susceptible to errors lasting multiple cycles. There were 420 errors recorded during tests with zero scale output. 125 windows out of those 420 (30%) showed multiple cycle errors. At full scale output 97 windows out of 1620 (6%) showed multiple cycle errors. Lower LETs showed a larger percentage of multiple cycle errors. At an LET of 58.7 MeV/(mg/cm^2) 51 windows out of 1020 (5%) showed multiple cycle errors. At an LET of 41.5 MeV/(mg/cm^2), 171 windows out of 1020 (17%) showed multiple cycle errors.

The likelihood that these are the result of more than one ion strike is very small. By multiplying the chip area by the flux, the number of ions striking the chip per second is calculated to be on average 852.5 ions/s. That means that an ion is hitting the device on average once every 1.2 milliseconds. These errors are occurring in cycles that are separated by only 2.5 µs. However, on rare occasion there are multiple errors in one window that are separated by a cycle or two that does not show any errors. An example of this is shown in Fig. 20. Errors should be occurring at approximately 2.5 µs intervals (not usually exact intervals since it was shown in Fig. 19 that the exact bits that are upset may change between cycles). In this case an error begins at roughly 2.5 µs, 7.5 µs, and 10 µs, but not at 5 µs.

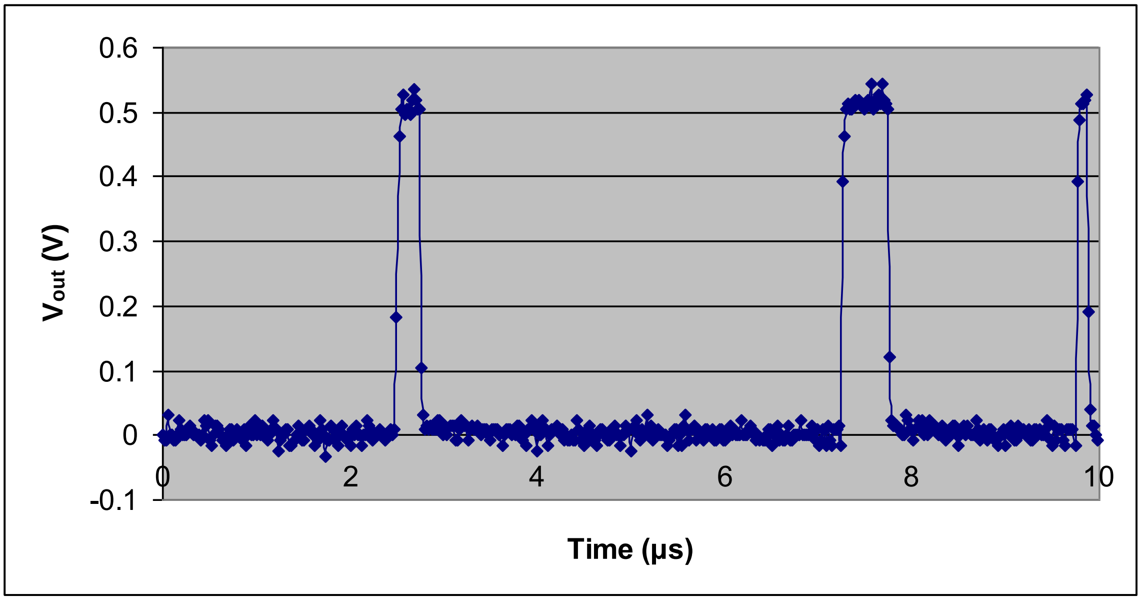


Fig. 20 Output of DUT 3 when irradiated with a 24.8 MeV/nucleon beam composed of Xe with a supply voltage of 5.25 V and a zero scale output. The output has 12 bits read out from the ADC in order from most significant to least significant, which takes 1.5 µs, and then 1 µs of zeros, and then the process repeats. All 12 bits of every output are supposed to be low. The first error begins at 2.5 µs and has two bits high, the second error begins at 7.25 µs and has four bits high, and the third error begins at 9.75 µs and has one bit high.

Some of the multiple cycle errors may be lasting for longer than 10 µs. The oscilloscope triggers whenever it notices an error and records 10 µs of data into permanent memory, 2.5 µs of data before the error and 7.5 µs after the error. In some of the windows, an error appears before the error at 2.5 μs, meaning that that particular error did not trigger the oscilloscope as an error. An example is shown in Fig. 21.

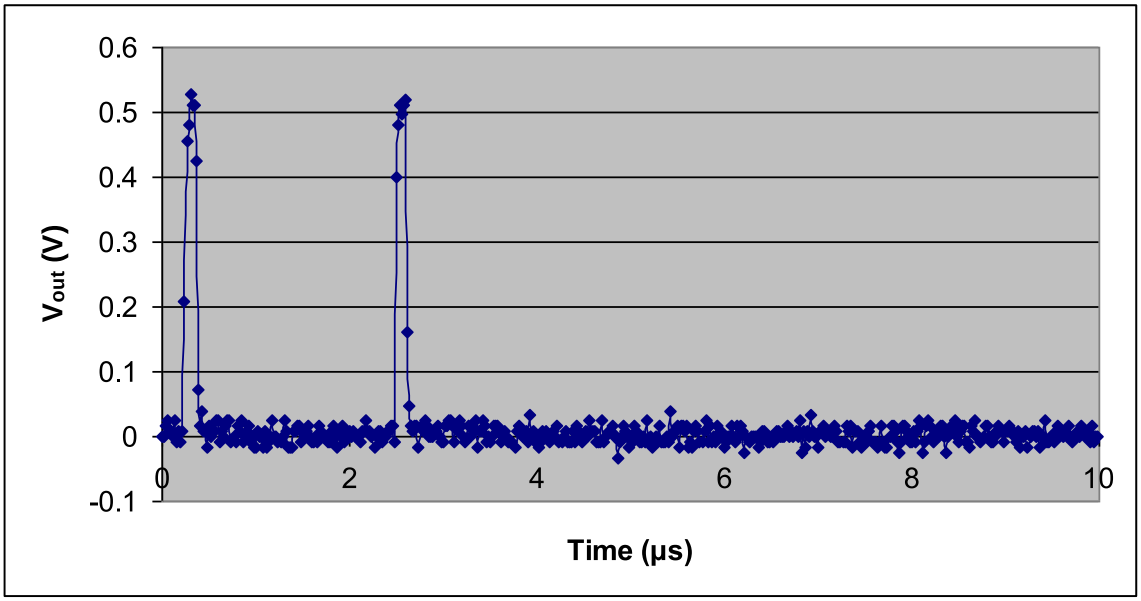


Fig. 21 Output of DUT 3 when irradiated with a 24.8 MeV/nucleon beam composed of Xe with a supply voltage of 5.25 V and a zero scale output. The two errors are single bit upsets. The first begins at 0.24 μs and the second begins at 2.5 μs, which is the trigger point.

The most likely interpretation of this is that the error happened too quickly after the end of the previous window, before the oscilloscope could prepare itself to trigger again. On average, it takes the oscilloscope 15 μs to prepare itself to trigger again after an error. There were two instances where it appeared that there might be four consecutive windows. If these windows are connected, this would mean that the results of a single ion strike lasted approximately 85 μs under these operating conditions. It should be noted that in some cases, the window previous to one containing a pre trigger error did not always show a repeating error. Unfortunately, there is no way to be sure whether any of the pre trigger errors are continuations of previous errors because the timestamp data for the windows could not be saved by the oscilloscope. To be conservative, each window was counted as a separate error even if a pre trigger error was visible.

G. Discussion of the difference in results between the two facilities

The difference seen in the results between testing at Berkeley and Texas A&M is still under investigation. There were a number of differences in the test setups between the two facilities. At Berkeley, testing was done in a vacuum chamber, which results in high background noise. It was necessary to push the inputs past the supply voltage rails in order to get stable outputs. At Texas A&M, since the testing is done in room air, the connections are more direct, and the output appeared to be more stable. However, due to limited test time, there was not enough time to establish a baseline. At Texas A&M, there were beam stability problems, and rf and the beam would constantly be lost during an ion run. This impacted the randomness of the beam, and increasing the possibility of the ion strikes occurring within a few microseconds. Testing at Berkeley was done with the DUT in the dark, while at Texas A&M, the DUT was exposed to room light.

The beam energy and ion penetration used at Texas A&M was significantly higher than at Berkeley. This difference was not expected to be significant as the product is built on a very low resistivity substrate and the active area of the product is only 12 µm deep from the surface of the die. Likewise, the multiple sample errors seen at Texas A&M were unexpected, as the part resets all analog circuitry between samples. However, until the differences in test results are understood, the worst case results should be the ones considered.

VI. Conclusions

The space level ADC128S102WGRQV is immune to Single Event Latchup at high temperatures (120-128°C) and maximum supply voltage up to an LET of at least 121.76 MeV/mg/cm^2 (the highest LET tested).

The LET threshold was found to be between 5.77 and 14.32 MeV/(mg/cm^2) for a supply voltage of 2.7 V and a full scale output at a beam energy of 4.5 MeV/nucleon. The LET threshold was not found for a supply voltage of 5.25 V.

Cross sections for a supply voltage of 5.25 V averaged 2 times higher than cross sections for supply voltages of 2.7 V or 3 V. Cross sections for full scale output were on average 6 times greater than those for zero scale output.

The worst case cross section was 4.14×10^{-5} cm^2. This occurred when the supply voltage was at 5.25 V, the output was at full scale, the beam energy was 24.8 MeV/nucleon, and the LET was 58.7 MeV/mg/cm^2.

The most likely bits to be upset were the least significant ones regardless of beam energy of operating conditions.

Differences in the SEU response were seen in testing at Berkeley and Texas A&M. Until the differences are fully understood, worst case results are being reported.

Appendix A

Heavy-Ion Beam Bragg Curves

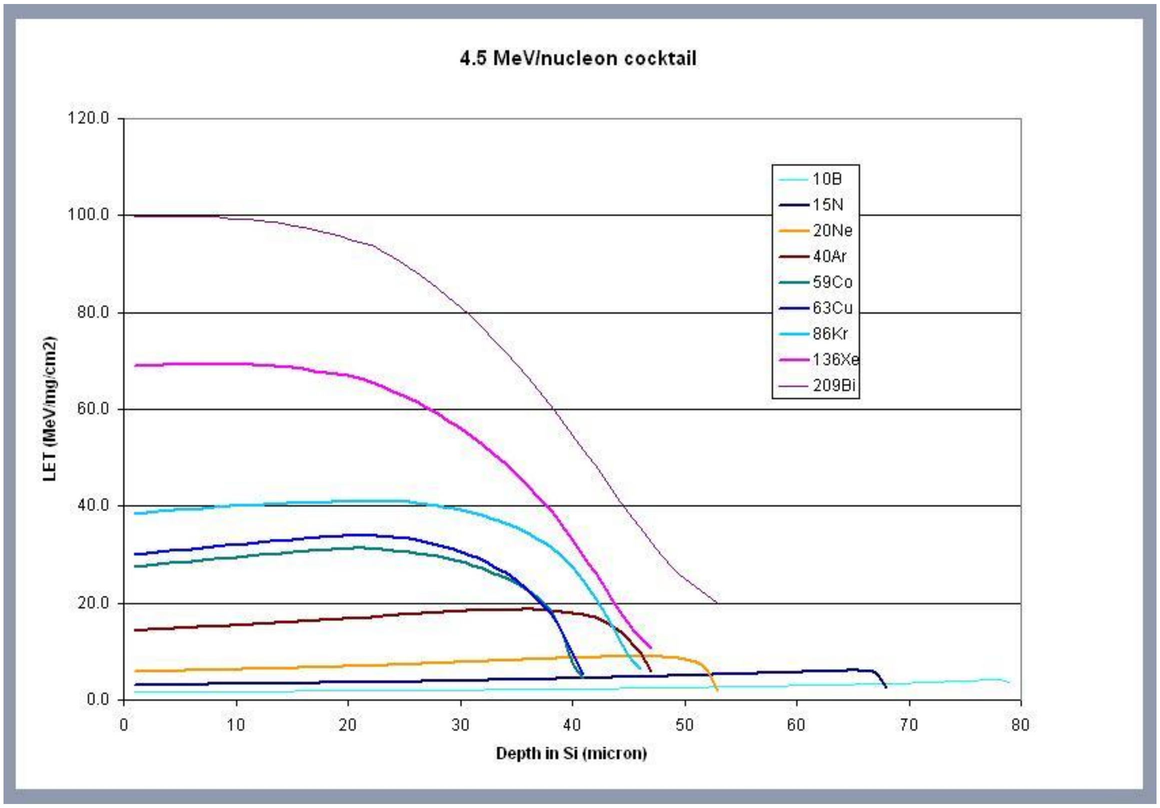


Fig. A1 LET vs. depth in silicon for various ion species used in testing at Berkeley for a 4.5 MeV/nucleon ion cocktail from [7]

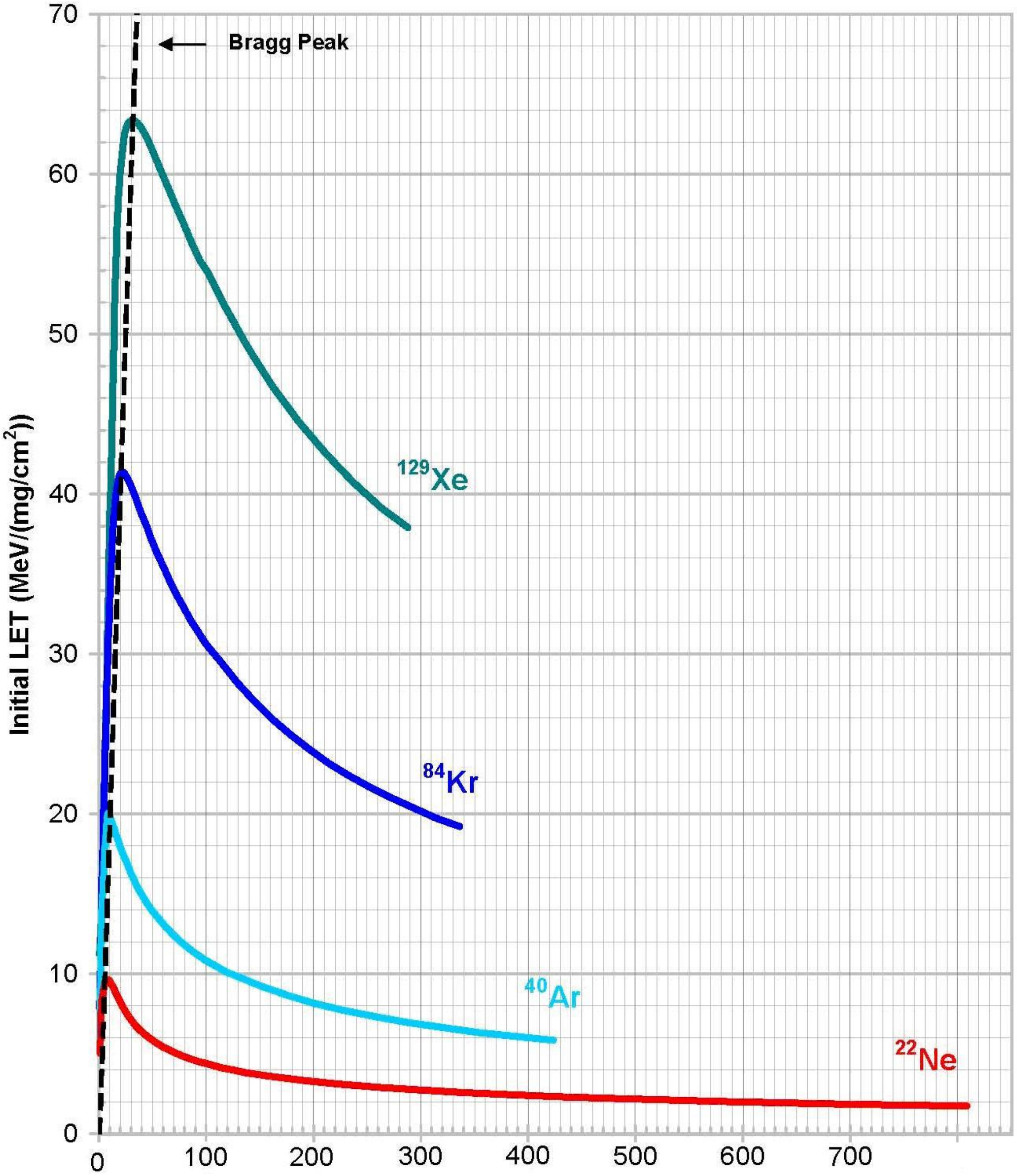


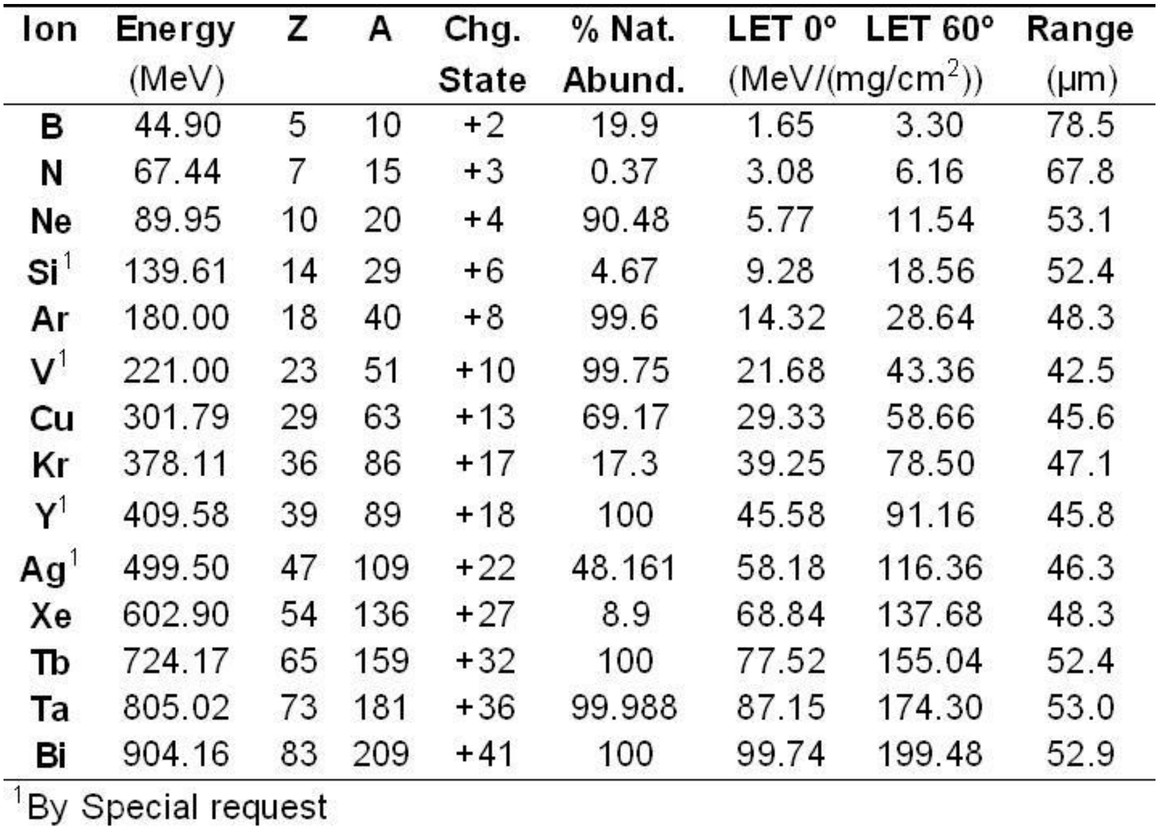
Fig. A2 LET vs. depth in silicon for various species used in testing at Texas A&M for a 24.8 MeV/nucleon ion beam. The x-axis is in µm. To read this chart start from the rightmost point on a line and trace left from [8]

Appendix B

4.5 MeV/nucleon beam

The cyclotron at Berkeley accelerates a variety of heavy ions, often called a cocktail, and then uses the cyclotron frequency to select a particular ion [9]. The cocktail used in testing had energy of 4.5 MeV/nucleon. The available ions are listed in Table B1.

Table B1
Heavy-ions available in the 4.5 MeV/nucleon cocktail at Berkeley from [9]



Ion	Energy (MeV)	Z	A	Chg. State	% Nat. Abund.	LET 0° (MeV/(mg/cm^2))	LET 60° (MeV/(mg/cm^2))	Range (μm)
B	44.90	5	10	+2	19.9	1.65	3.30	78.5
N	67.44	7	15	+3	0.37	3.08	6.16	67.8
Ne	89.95	10	20	+4	90.48	5.77	11.54	53.1
Si[1]	139.61	14	29	+6	4.67	9.28	18.56	52.4
Ar	180.00	18	40	+8	99.6	14.32	28.64	48.3
V[1]	221.00	23	51	+10	99.75	21.68	43.36	42.5
Cu	301.79	29	63	+13	69.17	29.33	58.66	45.6
Kr	378.11	36	86	+17	17.3	39.25	78.50	47.1
Y[1]	409.58	39	89	+18	100	45.58	91.16	45.8
Ag[1]	499.50	47	109	+22	48.161	58.18	116.36	46.3
Xe	602.90	54	136	+27	8.9	68.84	137.68	48.3
Tb	724.17	65	159	+32	100	77.52	155.04	52.4
Ta	805.02	73	181	+36	99.988	87.15	174.30	53.0
Bi	904.16	83	209	+41	100	99.74	199.48	52.9

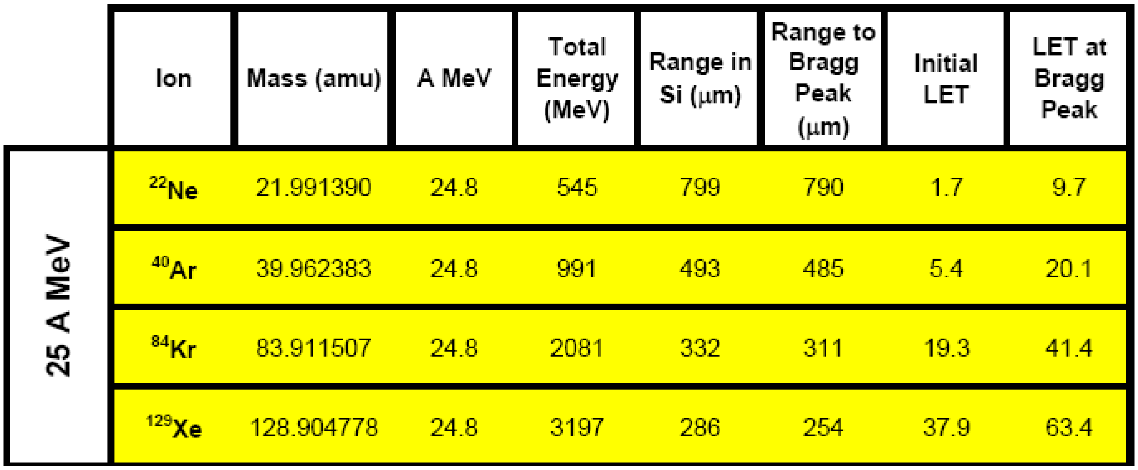
[1] By Special request

24.8 MeV/nucleon beam

Heavy ions at Texas A&M are supplied by one of two electron cyclotron resonance (ECR) sources that use high magnetic fields to trap plasma and high electric fields are used to extract ions [10]. The heavy ions at Texas A&M were available at higher energies. Table B2 shows the available ions at a beam energy of 24.8 MeV/nucleon.

Table B2

Heavy ions available at energy of 24.8 MeV/nucleon from [10]



	Ion	Mass (amu)	A MeV	Total Energy (MeV)	Range in Si (µm)	Range to Bragg Peak (µm)	Initial LET	LET at Bragg Peak
25 A MeV	^{22}Ne	21.991390	24.8	545	799	790	1.7	9.7
	^{40}Ar	39.962383	24.8	991	493	485	5.4	20.1
	^{84}Kr	83.911507	24.8	2081	332	311	19.3	41.4
	^{129}Xe	128.904778	24.8	3197	286	254	37.9	63.4

References

[1] "ADC128S102QML 8-channel, 500 kSPS to 1 MSPS, 12-bit A/D converter," National Semiconductor, Santa Clara, CA, May 17, 2010. http://www.national.com/profile/snip.cgi/openDS=ADC128S102QML

[2] 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.

[3] "Evaluation Board User's Guide, Low Power, Eight-Channel CMOS Analog to Digital Converter Family," National Semiconductor, Santa Clara, CA, February 2006.

[4] "National Semiconductor's WaveVision4 Data Capture System User's Guide", National Semiconductor, Santa Clara, CA, October 2006. http://www.national.com/appinfo/adc/files/WaveVision4p3UsersGuide.pdf

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[6] E. L. Petersen et al., "Rate Predictions for Single-Event Effects – Critique II", *IEEE Trans. on Nuclear Science*, Vol. 52, No. 6, December 2005, pp. 2158-2167.

[7] Lawrence Berkeley National Laboratory website, http://cyclotron.lbl.gov/Download.html

[8] Cyclotron Institute website, http://cyclotron.tamu.edu/ref/LET_vs_Range_25.pdf

[9] Lawrence Berkeley National Laboratory website, http://cyclotron.lbl.gov/subpage2.html

[10] Cyclotron Institute website, http://cyclotron.tamu.edu/ecr.htm