PROJECT
ESA_QCA0312S_C

TITLE
Heavy Ion Transients in Operational Amplifier of Type LM124, RH1014 and OP27

EUROPEAN SPACE AGENCY CONTRACT REPORT

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Class : Host System : Microsoft Word 97 for Windows, SE Macro Rev 3.0
Contract No : Host File : ...\D-PL-REP-5165-SE_iss1_final

SUMMARY

Single Event Transients induced by heavy ions have been measured for four different types of Operational Amplifiers operating in “comparator mode”. The Op-Amp types were LM124 form National Semiconductor and Texas Instrument, RH1014 from Linear Technology and OP27 from Analog Devices.
The two LM124 devices show about the same SET behaviour with SET pulses of about 40 µs maximum widths and a cross section of about 5E-3 cm2 starting at a LET of about 20 MeV/mg/cm2.
The radiation hard Op-Amp (RH1014) has about the same cross section as the LM124 but the LET threshold is rather high around a LET=30 MeV/mg/cm2. However, for higher LET values this device also show very long SET pulses, up to 300 µs long.

The Op27 is a fast Op-Amp with corresponding very fast SET pulses. No SET pulses above 1 µs were recorded for any LET value up to LET=59 MeV/mg/cm2.

The Op-Amps were tested with two different delta input voltages and no greater differences in cross section were observed. For RH1014, transients were detected with about 30% larger width for the low delta input voltage (?Vin = 0.2V) compared to the high delta input voltage (?Vin = 5V).

DOCUMENT CHANGE RECORD

Changes between issues are marked with a left-bar.

Issue	Date	Paragraphs affected	Change information
1	4 Feb 2004	All	New document

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1. INTRODUCTION

This report presents the results from heavy ion irradiation on four types of Operational Amplifiers (Op-Amps). Recorded parameters were the Single Event Transient (SET) pulse amplitude, pulse duration and the cross section as a function of Linear Energy Transfer (LET).
One of the Op-Amps has been tested in a voltage regulator application. Comparison of SET probabilities for the device in comparator mode and in application is given.

Heavy ion Irradiation has been performed at the HIF facility at CYCLONE, Universite´Catholique de Louvain in Belgium and at the RADEF facility at Jyväskylä in Finland.

2. TEST SAMPLES

Table 1 below summarises data for the test samples used. In those cases where the test samples have four integrated amplifiers in each package, only one of the amplifiers has been tested.

TABLE 1 TEST SAMPLE DATA

Part Type	LM124	RH1014	LM124	OP27A
Manufacturer	National Semi	Linear Tech	Texas Inst	Analog Devices
Date Code	9652	9651	0207	0021
Package	DIL-14	FP-14	FK-18	TO99
Sample Size	1	1	1	1
Part Number				
Quality Level	Class S	Class S	Mil Temp	Class S
Slew rate	0.5 V/µs	0.2 V/µs	0.5 V/µs	2.8 V/µs
Amplifiers per package	4	4	4	1

3. TESTING TECHNIQUE

Single Event Transients (SET) was measured with two oscilloscopes (Tektronix TDS3054, 500 MHz, 5GS/s) in order to record both negative and positive SET pulses. For each SET the pulse width and amplitude were registered on a computer. The process time per event is about 20 ms. To avoid dead time in the system the flux of the heavy ion beam was adjusted with respect to the upset rate. The test software was developed by use of "Labview software" for the GPIB communication between the PC and the oscilloscope and to store all results.

3.1 Bias Condition and Test Set-up for the Comparator

All four devices were tested in the same way, supplied from a single voltage supply of +15 VDC. In Fig 3.1.1 below a schematic drawing of the test set-up is shown. All Op-Amp's have been tested in comparator mode with 0.2V and 5V delta-input voltage, see Table 2.
For LM124 from National Semiconductor SET data were measured with and without an extra capacitance load (30 nF) connected parallel to R6.

TABLE 2 BIAS CONDITIONS FOR THE OP-AMPLIFIERS.

Input bias			
?Vin (V)	**V+ (V)**	**V- (V)**	**Vout (V)**
0.2	**2.70**	**2.50**	**12**
5	**7.43**	**2.50**	**12**

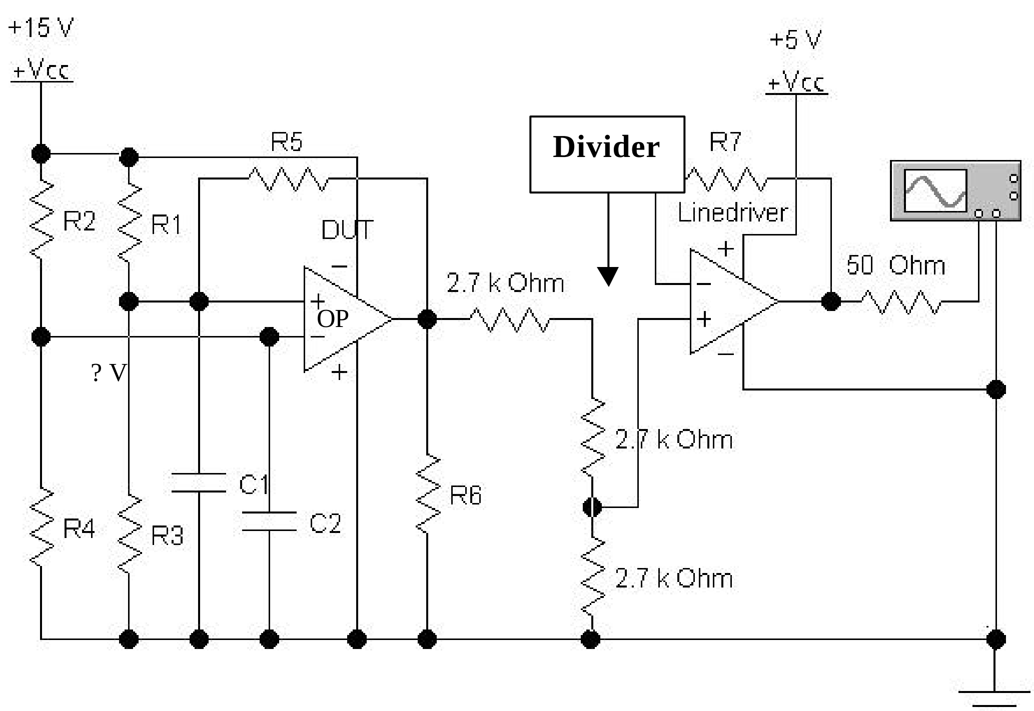


Fig 3.1.1 Schematic draws of the test set-up. The resistance dividers R1/R2 and R3/R4 maintain input voltage differences. The box to the right represents the oscilloscope with 50 O input resistance. R1 = 26.1 kO or 5.72 kO, R2 = 26.1 kO, R3 = 5.62 kO, R4 = 5.23 kO, R5 = 562 kO, R6 = 38.4 kO, R7 = 24 O, C1 = 3.3 nF and C2 = 150 nF.

3.2 Definition of the Detected Transients

The outputs of all four Op-Amp’s have a voltage divider of three resistors, resulting in one third of the real voltage level on the line driver input (see Fig 3.1.1). The line driver output has a serial resistor of 50 ohm and the oscilloscope input is set to 50 ohm, therefore the measured signal by the oscilloscope is one half of the input on the line driver. Thus all measured amplitudes have to be multiplied with a factor of 6.

In Fig 3.2.1 below the DC level is at about 4 (div) x 0.5 (V/div) x 6 = 12 V.
The pulse width is measured according to the oscilloscope specifications at the Full Width at Half Maximum (FWHM) of the negative measured amplitude. The total length of the pulse at nominal DC level is much longer.

In the off-line data analysis the SET probability and the associated pulse width could be determined for any value of the SET amplitude.

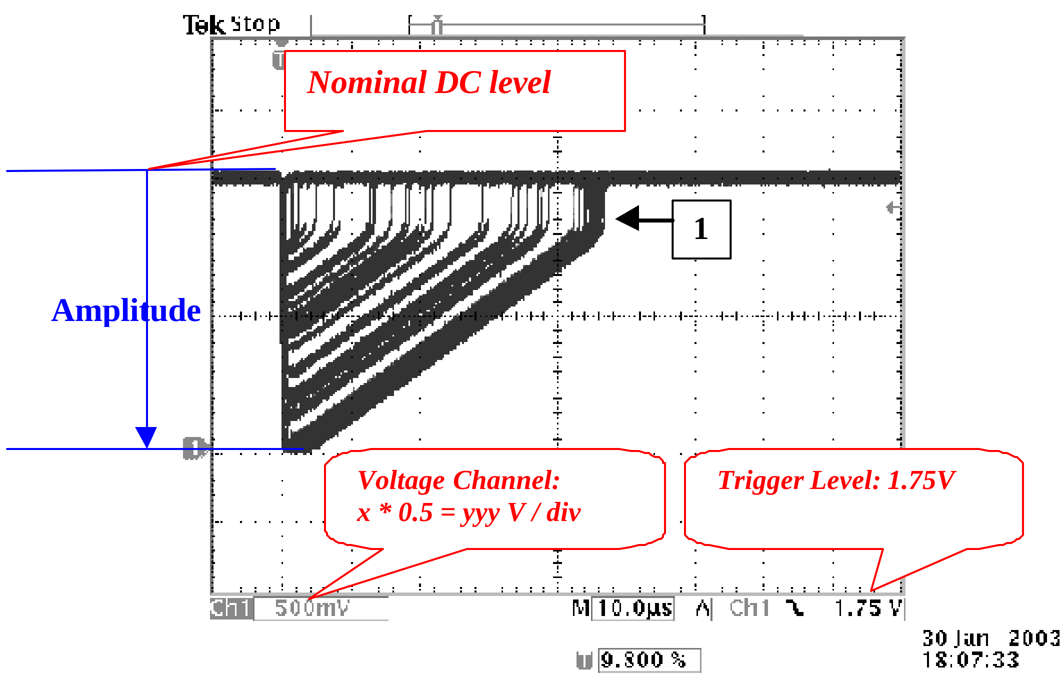


Fig 3.2.1 Definition of the amplitude of the SET pulses. This rapidly rising slope up to nominal DC level marked in the figure above with "1", have afterwards been found out to depend on the line-driver. The long cables gave rise to a little loss of voltage to the drivers, so the drivers could not operate fully "rail-to-rail". This has later been confirmed with tests in our laboratory. This effect occurred only during the investigation at Jyväskylä in Finland.

4. HEAVY ION TEST FACILITY

Heavy ion tests were performed both at the CYClotron of Louvain la Neuve (CYCLONE) in Belgium and at the Cyclotron at the University of Jyväskylä in Finland. The heavy ions and the corresponding LET values used at the two facilities are given in Table 3 and 4, respectively.
Data have been recorded for normal incident angle as well as tilted angles.

TABLE 3 HEAVY IONS USED AT LOUVAIN LA NEUVE IN BELGIUM

Element	Energy [MeV]	Tilt Angle [Deg]	LET value [$MeV/mg/cm^2$]	Range [µm]
Ne	78	0	5.85	45
Ne	78	54	10	
40 Ar	150	0	14	42
40 Ar	150	40	18.7	
40 Ar	150	54	24	
78 Kr	316	0	34	43
78 Kr	316	41	45	

TABLE 4 HEAVY IONS USED AT JYVÄSKYLÄ IN FINLAND.

Element	Energy [MeV]	Tilt Angle [Deg]	LET value [$MeV/mg/cm^2$]	Range [µm]
Si	280	0	7.0	127
Si	280	48	11	
Si	280	60	14	
Fe	523	0	18	95
Fe	523	40	24	
Fe	523	52	29	
Kr	766	0	29	93
Kr -Au foil		0	30	
Kr -Au foil		40	40	
Kr	766	48	44	
Kr -Au foil		50	47	
Kr	766	60	59	

5. RESULTS

The Op-Amp's have been tested in comparator mode using two different delta input values with the comparator output being high. When the comparator output is high all recorded SET pulses will be negative. Consequently the pulses are going from the maximum output DC level at around 12 Volt towards the ground level. The oscilloscope trigger was set to 1.75 V filtering out all negatives pulses with smaller amplitude.

Results are presented as the cross section versus the LET value. Diagrams showing the distribution of the number of events versus the pulse duration and the average and maximum amplitudes versus the LET value are given. Scatter diagrams of the pulse width versus the pulse amplitude are given for representative LET values and an oscilloscope image from the same run.
In all cross-section diagrams where runs have been made both for Kr (LET = 29.4) and Fe (LET = 29.2) a small difference are found in the cross-sections. The cross-sections are higher for Fe. The range in Silicon for the two ions is about the same. The reason for the difference is likely due to uncertainties in the monitoring of the beam intensities. Detailed test run data and information are given in Appendix A

From all four Op-Amps, the oscilloscope images are more or less similar. The main differences are in the pulse duration and in the cross-sections. OP27 with very short SET pulses differ most from the other.
The shape and differences between the SET pulses resulting from heavy-ion deposit charge in the operational amplifiers can be explained by parameters such as the output sink value and the Slew Rate (SR).
The fall time depends on the Op-Amp's capacity to sink the existing loaded charge. With a 15pF capacitor charged to 12V and a typical current sink value of 15mA, the fall time will be 12ns. In reality the fall time is longer due to the Op-Amp reset time.

The inclination of the straight slope is believed to depend only on the actual Op-Amp slew rate. In Fig.5.1.5 the calculated slew rate for LM124 is found to be 0.23 V/µs. This is about a factor of 2 lower than the specification value. A decreasing effect of the slew rate has been observed by increasing irradiation on the samples. However, the measured difference between the first and the last test run is only in the order of 10%.
The measured value for LM124 from TI fits better to specification value.
For RH1014, the difference in specified slew rate and measured slope from the transients differs by a factor of 10. To fit the specification slew rate the pulse width should not be longer than about 50 µs FWHM. Thus, there must be other phenomena in the heavy ion transients that mask the slew rate.

TABLE 5
SLEW RATE VALUES FIRST TEST RUN (SR1) LAST TEST RUN (SR2) AND SPECIFICATION (SR).

Device	SR1 (V/µs) Measured	SR2 (V/µs) Measured	SR (V/µs) Specification
LM124NS	0.23	0.21	0.5
RH1014	0.024	0.019	0.2
LM124TI	0.40	0.39	0.5
OP27	5.0		2.8

5.1 LM124 NS, No Load

The cross section for LM124 from National Semiconductor is shown in Fig 5.1.1. No significant differences in SET sensitivity between the two delta-input voltages 0.2 V and 5V could be observed. The cross sections for SET pulses with pulse widths >10 µs are shown in Fig 5.1.1 for comparison

From LET = 18 MeV/mg/cm^2 and higher, SET pulses were observed with the maximum voltage swing (to ground level), see Fig 5.1.2.
SET pulse widths up to 35 µs were measured, see Figs 5.1.4 to 5.1.7.
The data shown in the scatter diagram Fig 5.1.4 and 5.1.6 indicate that amplitudes and pulse widths correlate up to nearly 12 V. When the maximum amplitude is reached, the pulse width still increases.
In Figs 5.1.3, the distribution of SET pulse widths for LET=29 MeV/mg/cm2 are shown. The distribution indicates two main groups of pulse widths that are more frequent than others.

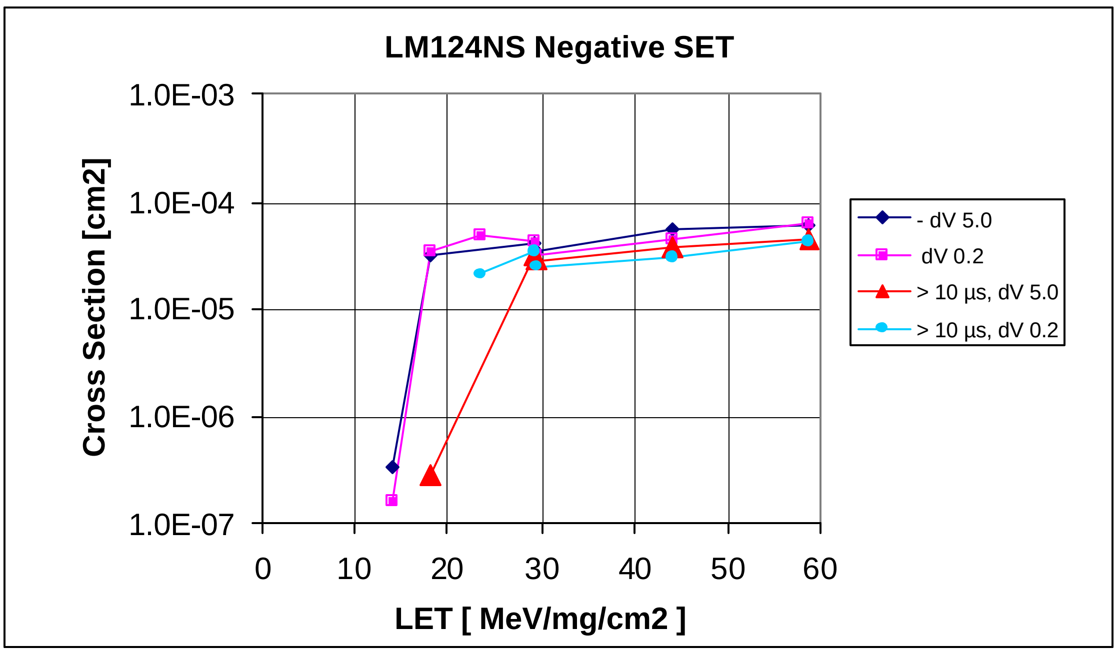


Fig 5.1.1 SET cross-section versus LET-value for two different pulse lengths, all pulses and pulses longer than 10 µs. The results are given for the two delta input voltages, 0.2V and 5.0V.

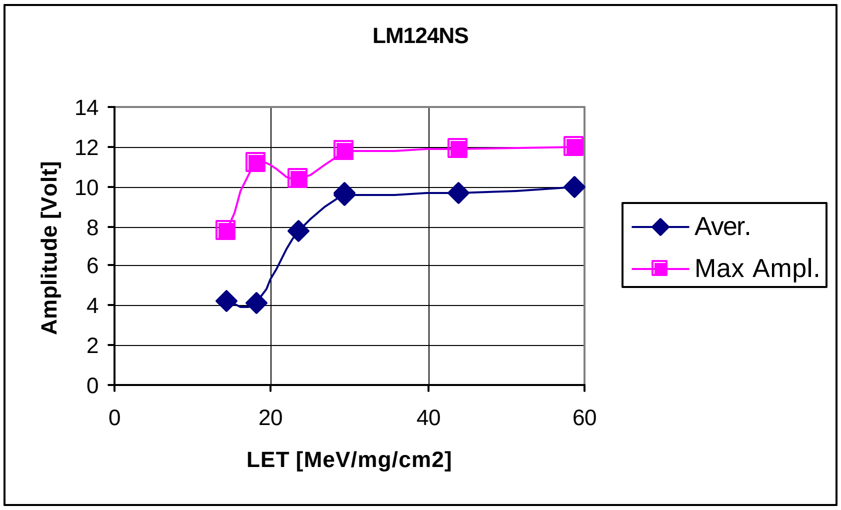


Fig 5.1.2 Average and Max amplitudes versus the LET-value.

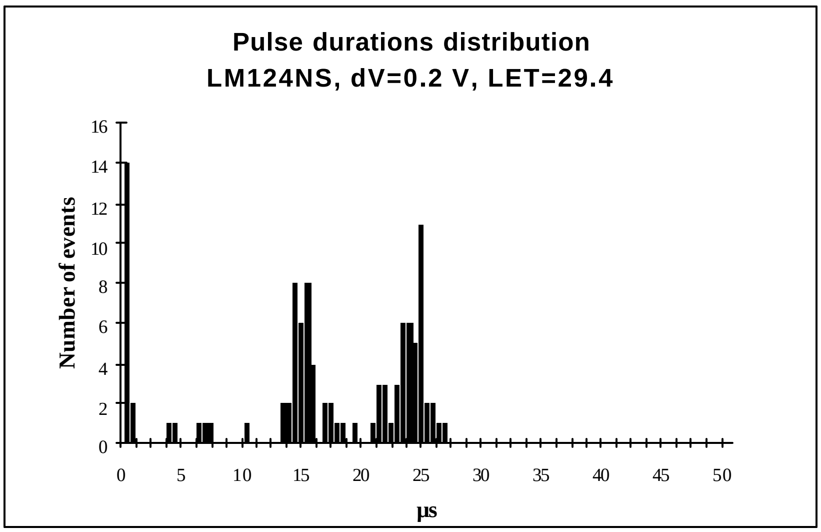


Fig 5.1.3 The distribution of the events versus the pulse duration.

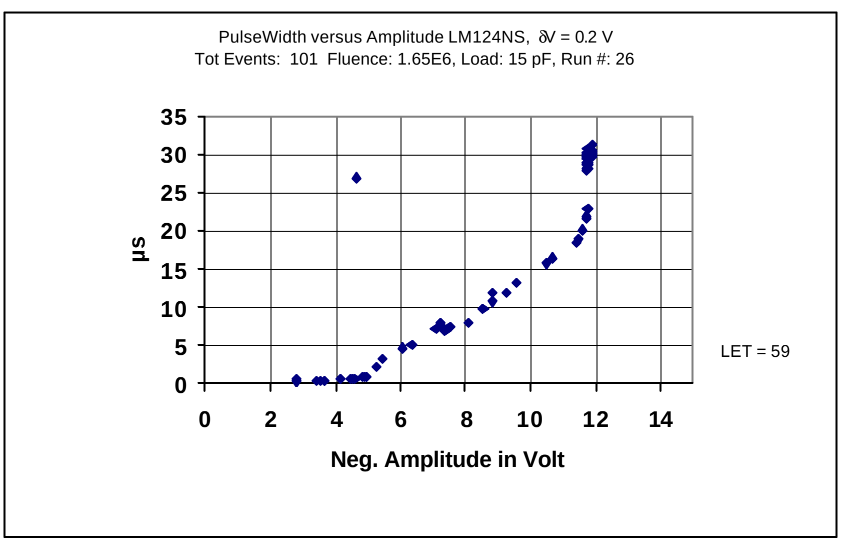


Fig 5.1.4 Scatter diagram showing SET pulse FWHM vs. the amplitude in Volt, with delta input voltage = 0.2 V.

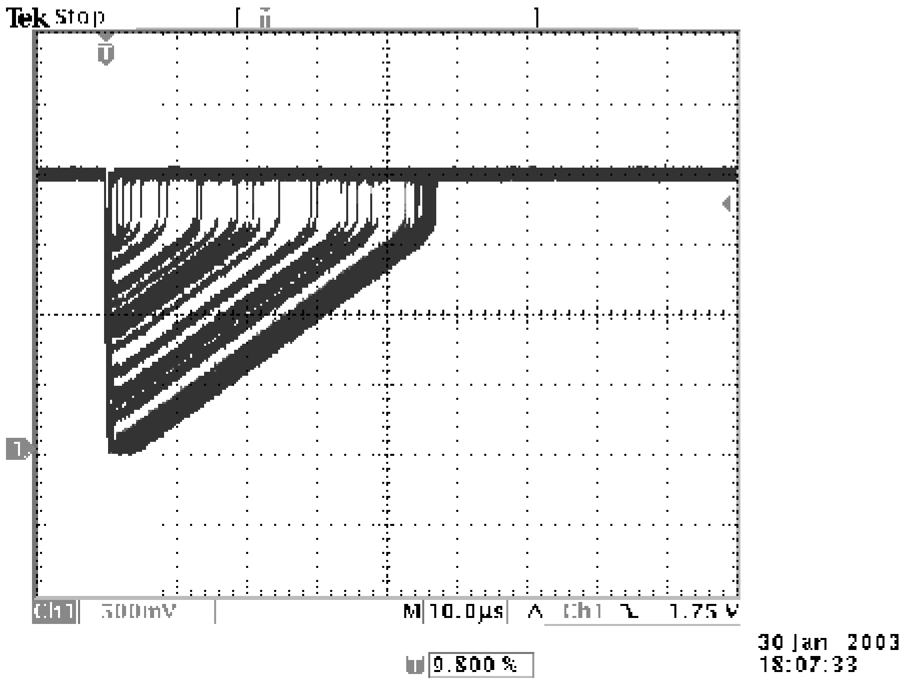


Fig 5.1.5 Oscilloscope picture showing the SET pulses given in figure 5.1.4

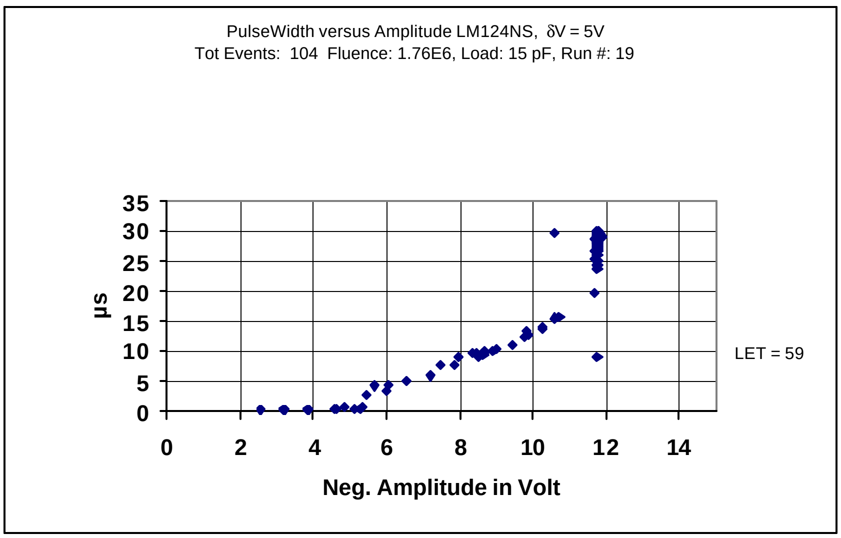


Fig 5.1.6 Scatter diagram showing SET pulse FWHM vs. the amplitude in Volt, with delta input voltage = 5 V.

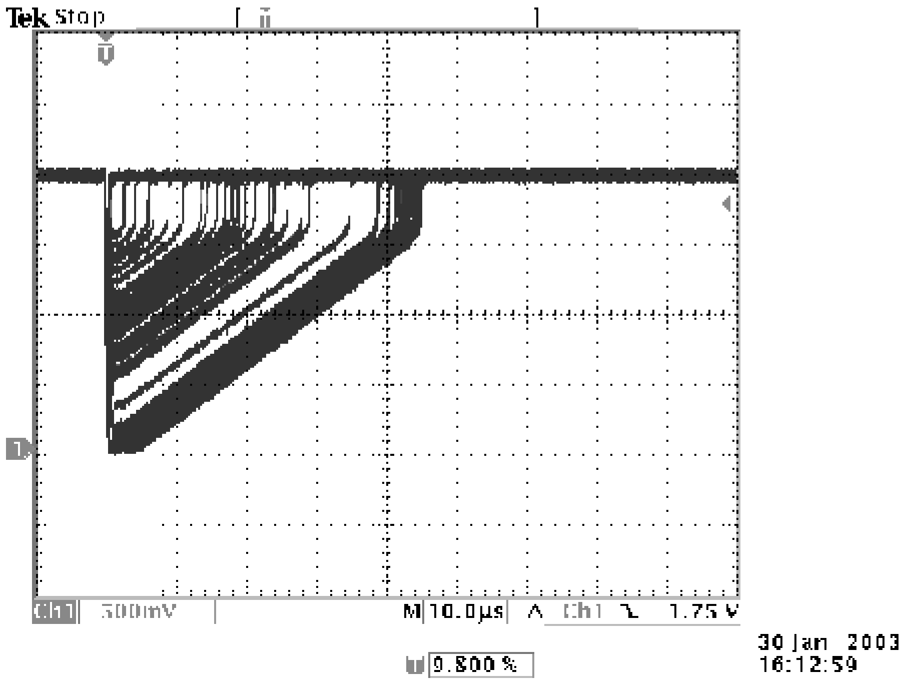


Fig 5.1.7 Oscilloscope picture showing the SET pulses given in figure 5.1.6

5.2 LM124 NS, Load of 33 nF

LM124 NS was tested with a load of 33 nF connected direct on the output of the Op-Amp to ground. No event was observed for a fluence of more than 2E+6 ions/cm^2 for any of the two delta input voltages, 0.2 or 5 Volt at LET = 59 MeV/mg/cm^2.
With a load of 33 nF the capacity is too low to sink the up charged capacitor seen in figure 5.2.1. A capacitor of 33 nF charged to 12 Volt will contain 4E-7 Coulomb of stored charge. With a sink value of 15 mA (acc. specification) the discharge time will be 26 µs. This should be compared with a SET time of maximum 10 ns so therefore no pulses are expected.

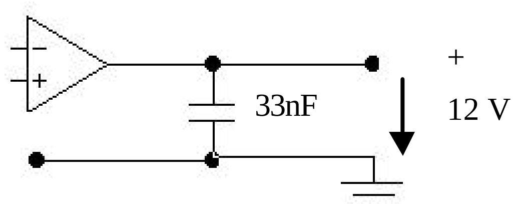
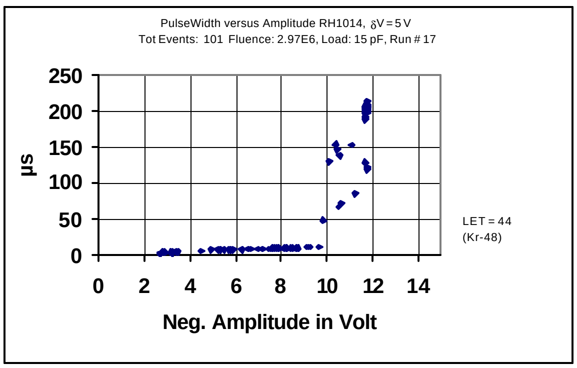


Fig 5.2.1 Schematic draws of the DUT with the load.

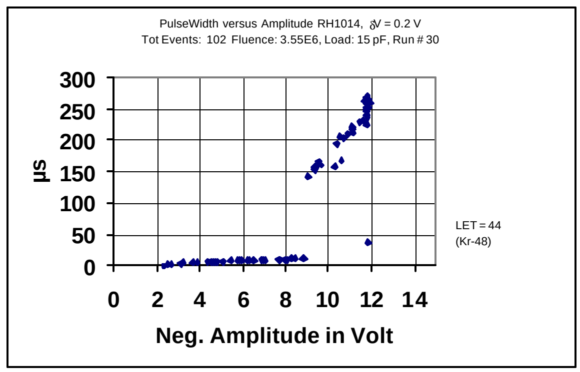
5.3 RH1014

The cross-section for RH1014 is lower than for LM124NS except for high LET values, see Fig 5.3.2. In the pictures of Fig 5.3.1 it can be seen that there are only the SETs with larger amplitudes than 9 V, which give rise to the very long pulse widths. Fig 5.3.1 a-d show the results for LET = 44 MeV/cm^2/mg. For LET=59 MeV mg/cm2, pulse widths of more than 300 µs have been observed, see Fig 5.3.5-5.3.7.

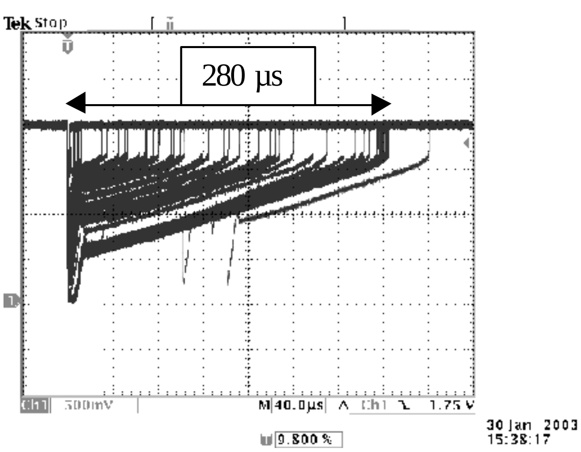
Distributions of pulse widths for LET=28 MeVmg/cm2 shown in Fig 5.3.4, indicate that it is only a small portion of all transients that result in long duration.
Differences between the two delta-input voltages could be observed in the pulse widths. With ?V_{in} = 0.2 V longer pulse lengths are observed and this tendency is significant from LET = 28 MeV/cm^2/mg and above. For ?V_{in} = 0.2 V pulse duration's up to 360 µs were observed, while for ?V_{in} = 5 V maximum duration's detected were up to 280 µs.



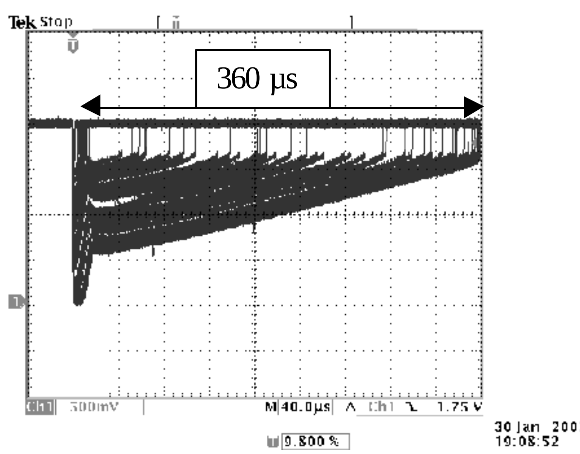
a/ Scatter diagram when ?V_{in} = 5 V



c/ Scatter diagram when ?V_{in} = 0.2 V



b/ Oscilloscope image when ?V_{in} = 5 V



d/ Oscilloscope image when ?V_{in} = 0.2 V

5.3.1 Scatter diagrams and oscilloscope images for LET = 44 MeV/cm^2/mg, which show the differences between the delta input voltages

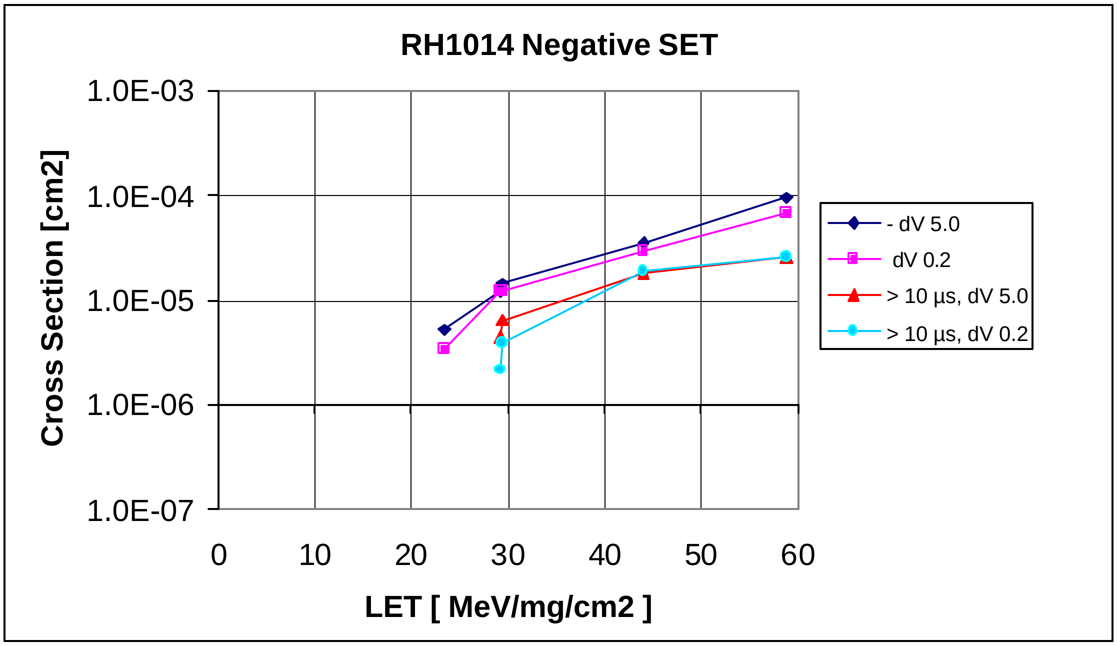


Fig 5.3.2 SET cross-section versus LET-value for two different pulse lengths, all pulses and pulses longer than 10 µs. The results are also given for the two delta-input voltages 0.2V and 5.0V.

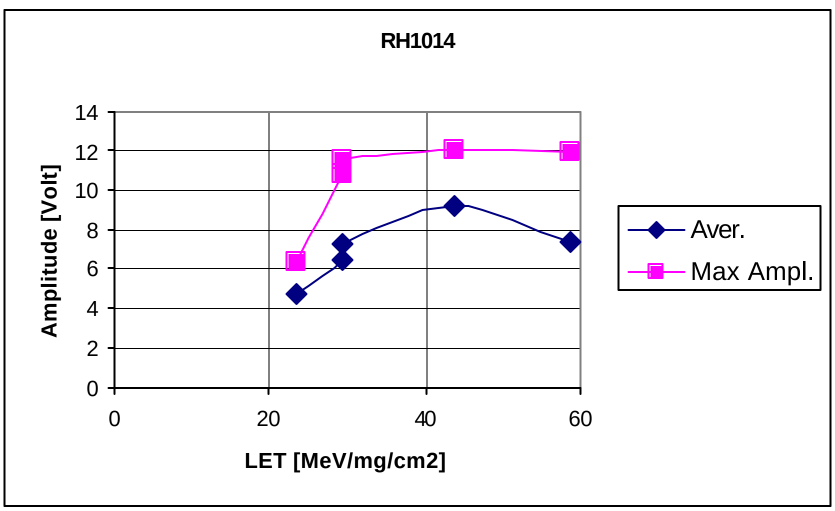


Fig 5.3.3 Average and Max amplitudes versus the LET-value.

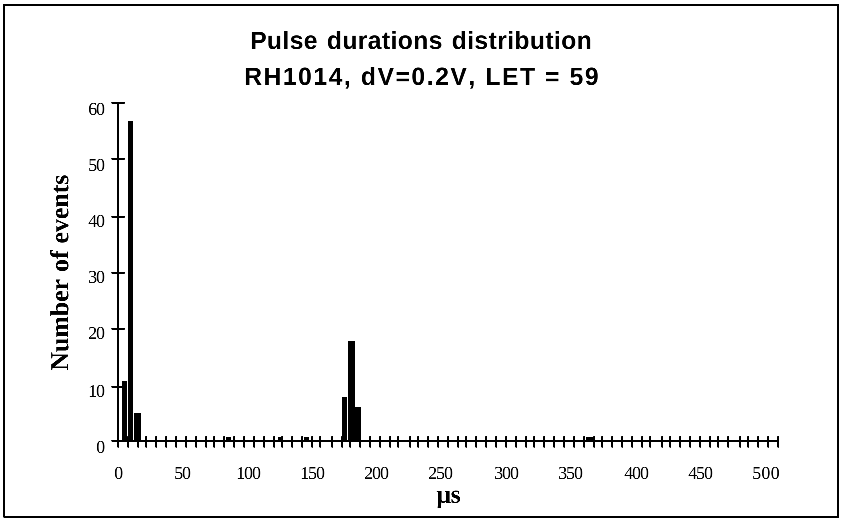


Fig 5.3.4 The distribution of the events versus the pulse duration.

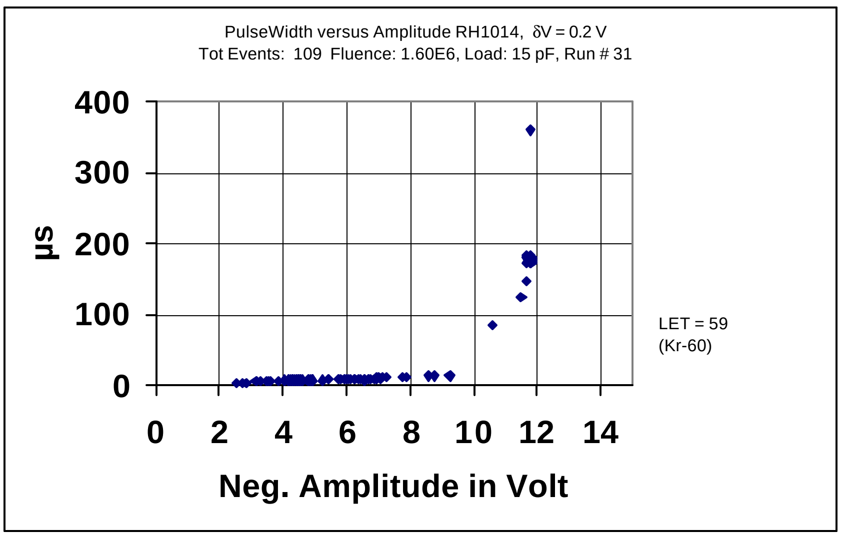


Fig 5.3.5 Scatter diagram showing SET pulse FWHM vs. the amplitude in Volt, with delta input voltage = 0.2 V.

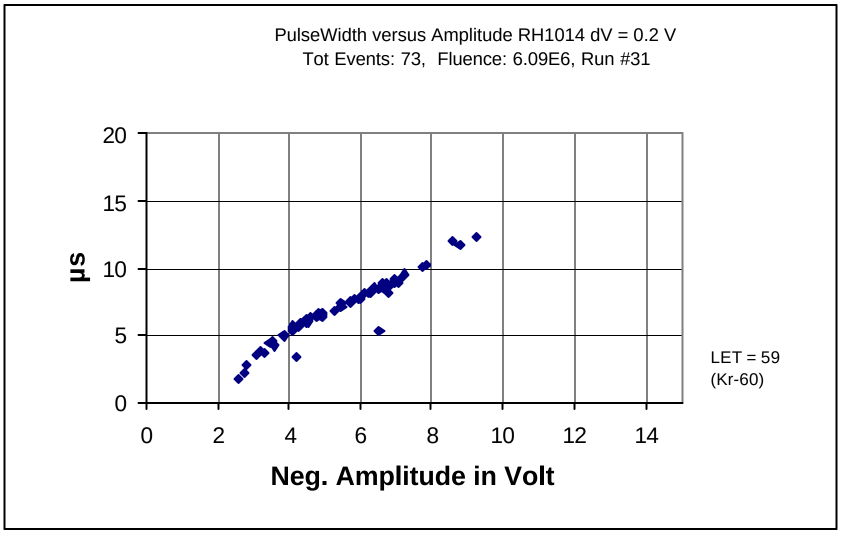


Fig 5.3.6 Scatter diagram from the same run #31 as in figure 5.3.4, where all events <20 µs are included.

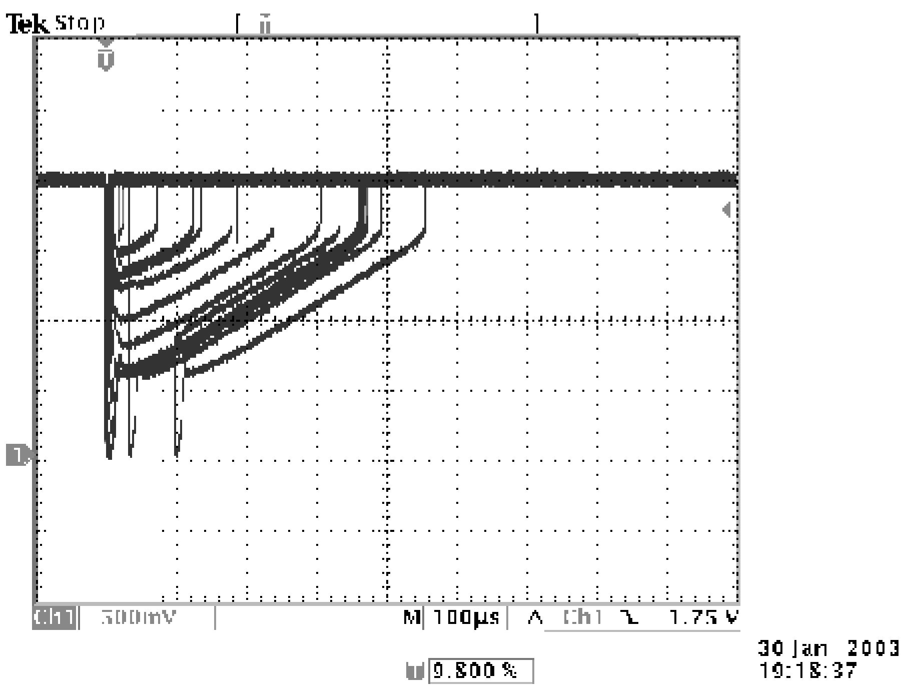


Fig 5.3.7 Oscilloscope picture showing the SET pulses given in figure 5.3.5 and 5.3.6

5.4 LM124 TI

LM124 from Texas Instrument have a cross-section as shown in Fig 5.4.1, very similar to LM124 from National Semiconductor. A major difference compared to LM124 NS and RH1014 is the shorter pulse widths. The maximum pulse width observed is about 25 µs, see Figs 5.4.3 and 5.4.4.
Pulses up to the maximum amplitude were observed from about LET = 24 MeV/mg/cm^2 and higher, see Fig 5.4.2.
No significant differences can be observed between the two different delta input voltages.

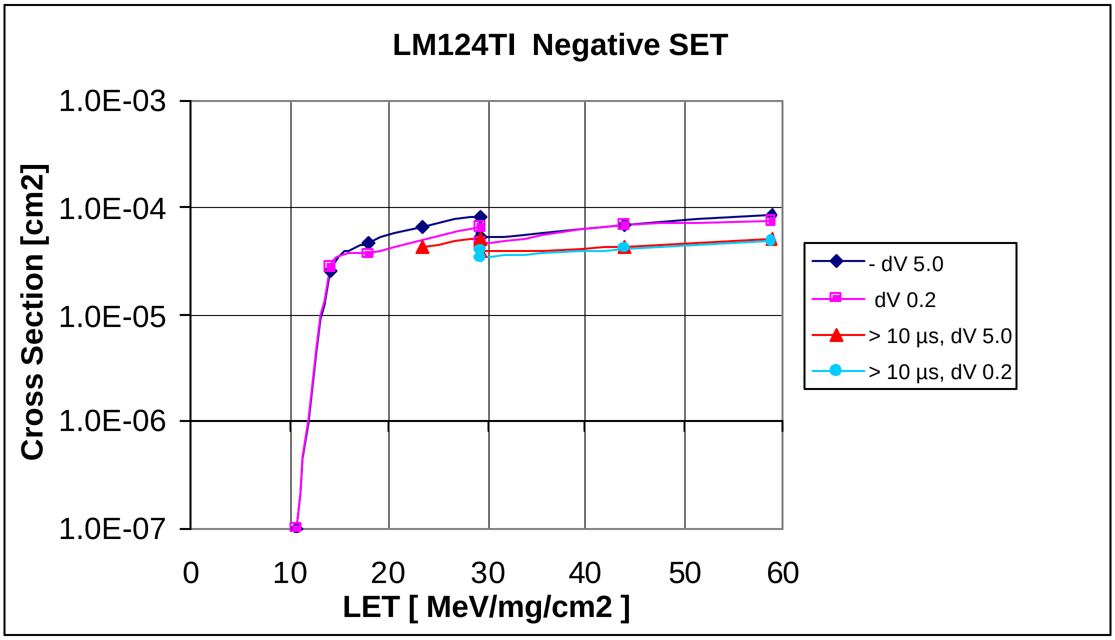


Fig 5.4.1 SET cross-section versus LET-value for two different pulse lengths, all pulses and pulses longer than 10 µs. The results also are given for the two delta input voltages 0.2V and 5.0V.

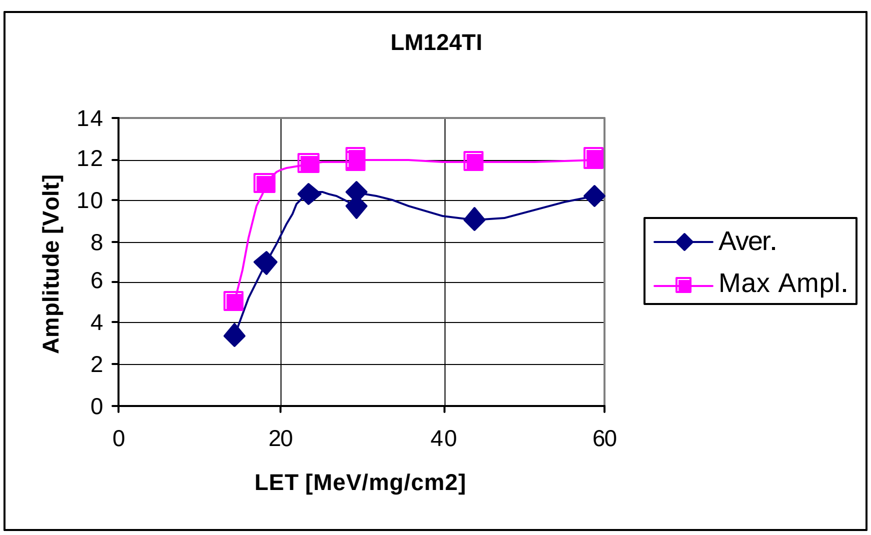


Fig 5.4.2 Average and Max amplitudes versus the LET-value.

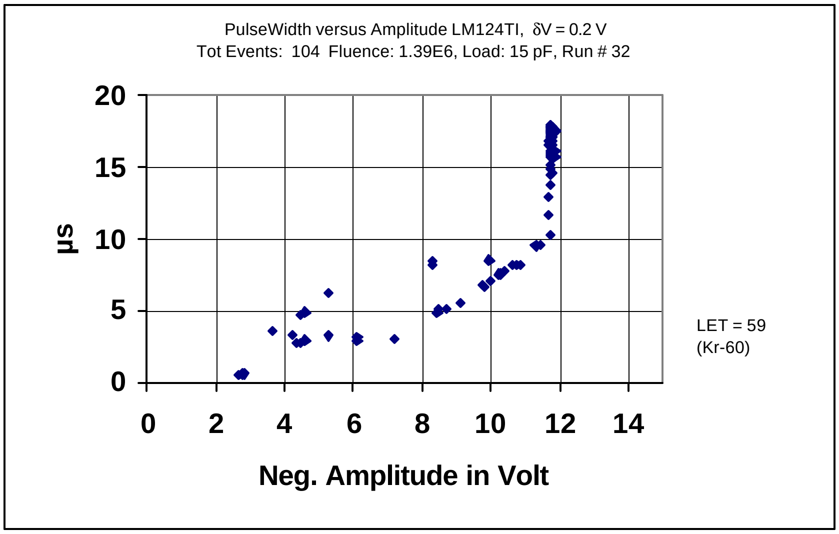


Fig 5.4.3 Scatter diagram showing SET pulse FWHM vs. the amplitude in Volt, with delta input voltage = 0.2 V.

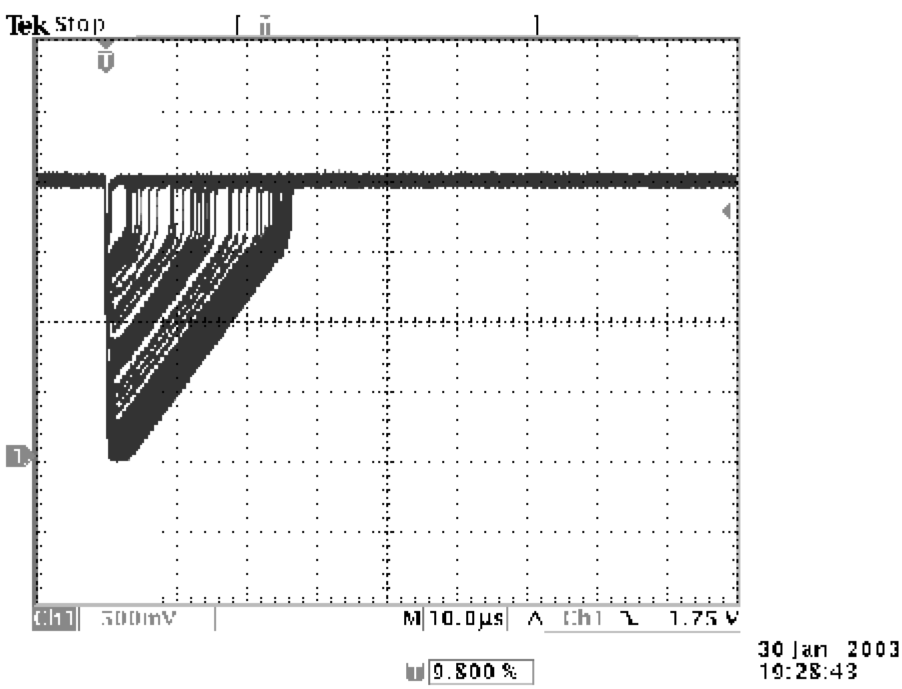


Fig 5.4.4 Oscilloscope picture showing the SET pulses given in figure 5.3.4

5.5 OP27A

OP27 indicate to be insensitive for a majority of the heavy ions. The largest measured amplitude was about 5 V with a pulse width of about 50 ns. A cross section of 3E-6 cm^2 was measured for LET = 59 $MeV/mg/cm^2$.
Scatter diagrams and oscilloscope pictures for 0.2V input difference are given in Fig 5.5.1 and 5.5.2, respectively. An observable correlation between the amplitude and the duration is for this Op-Amp observed for larger amplitudes than 1.5 Volt in figure 5.5.3 and 5.5.4

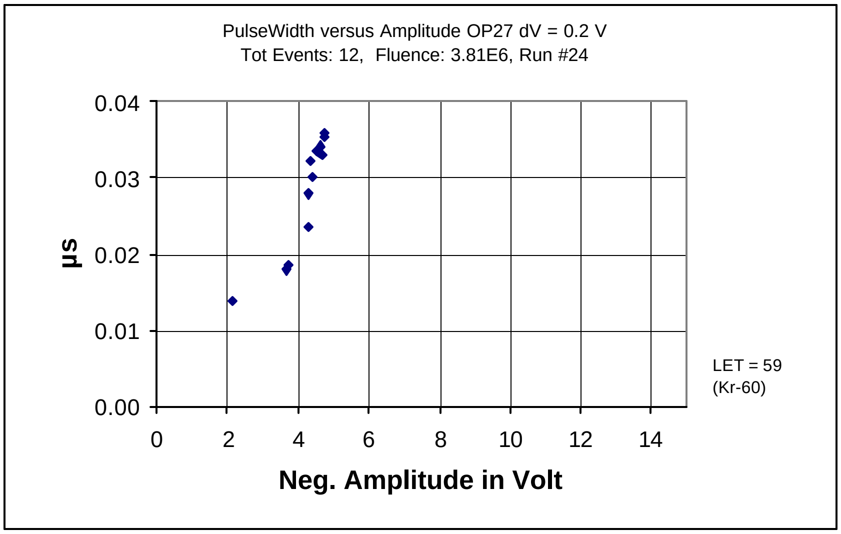


Fig 5.5.1 Scatter diagram showing SET pulse FWHM vs. the amplitude in Volt, with delta input voltage = 0.2 V.

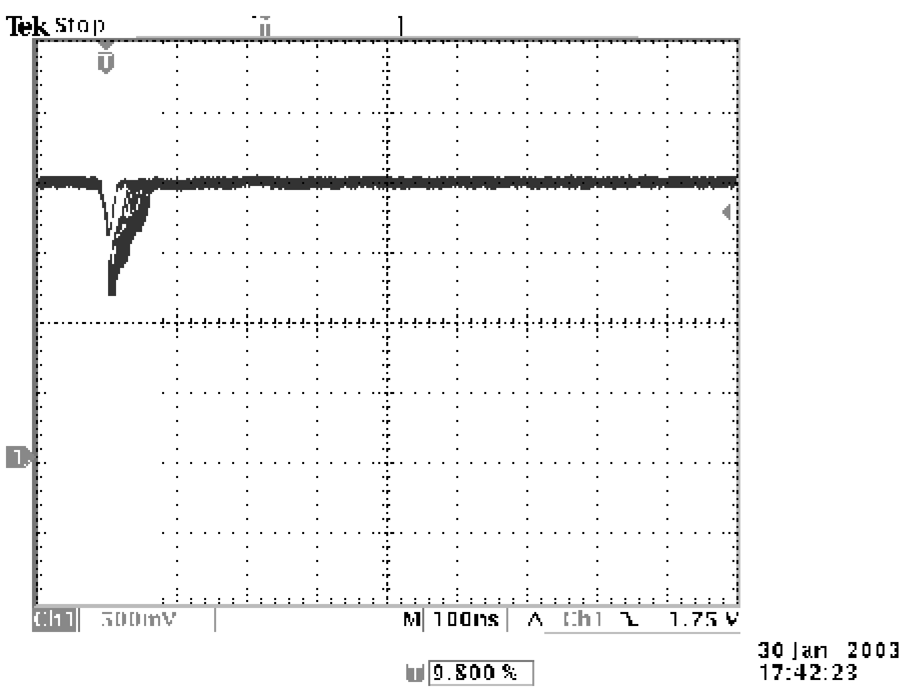


Fig 5.5.2 Oscilloscope picture showing the SET pulses given in figure 5.5.1

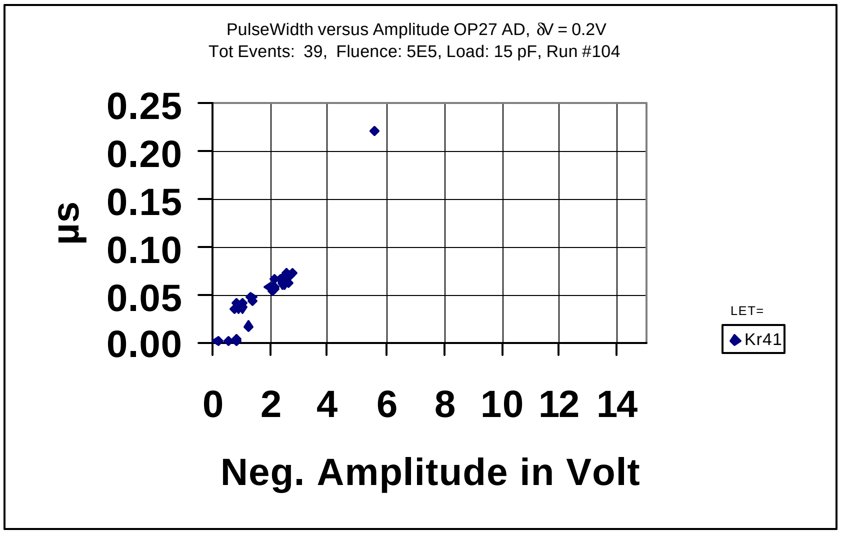


Fig. 5.5.3 *Scatter diagram showing SET pulse FWHM vs. the amplitude in Volt, with delta input voltage = 0.2 V. (LET = 45 MeV/mg/cm²)*
This is from the campaign at the CYClotron of Louvain la Neuve

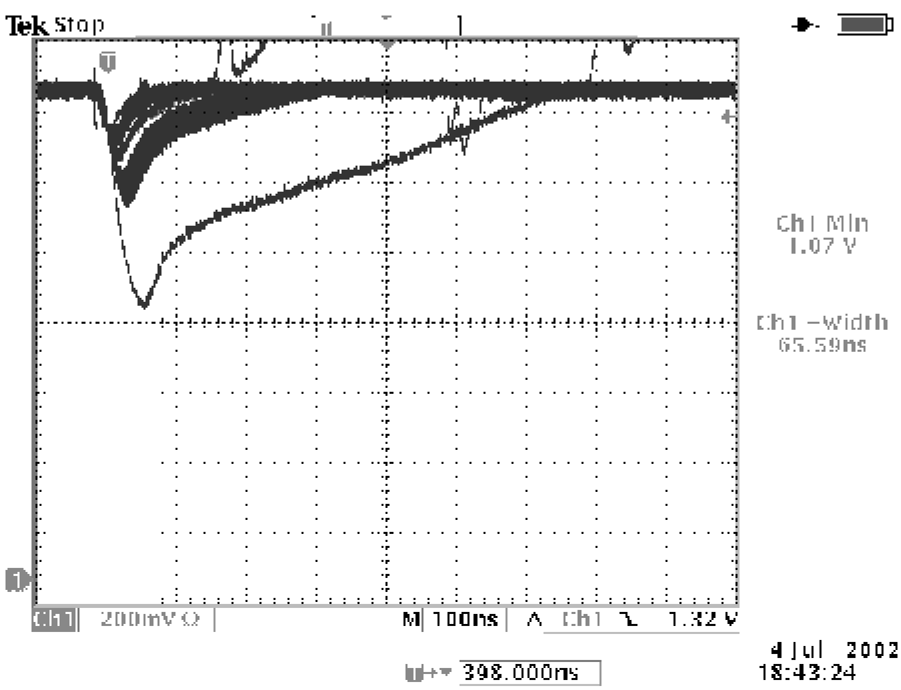


Fig 5.5.4 *Oscilloscope picture showing the SET pulses given in figure 5.5.3*

6. TRANSIENTS in a 5V POWER APPLICATIONS

6.1 5 Volt Regulator Application Set-Up

In a 5-Volt regulator set-up, shown in Fig 6.1.1, the Op-Amp LM124NS was irradiated and the output response was measured at testpoint TP1, as indicated in Fig 6.1.1. In this application LM124NS operate in a kind of linear mode to regulate the transistor output level to 5 V. The positive input is connected to a 2.5 volt zener diode reference, while the negative input sense the output voltage via the voltage divider R2 & R3.

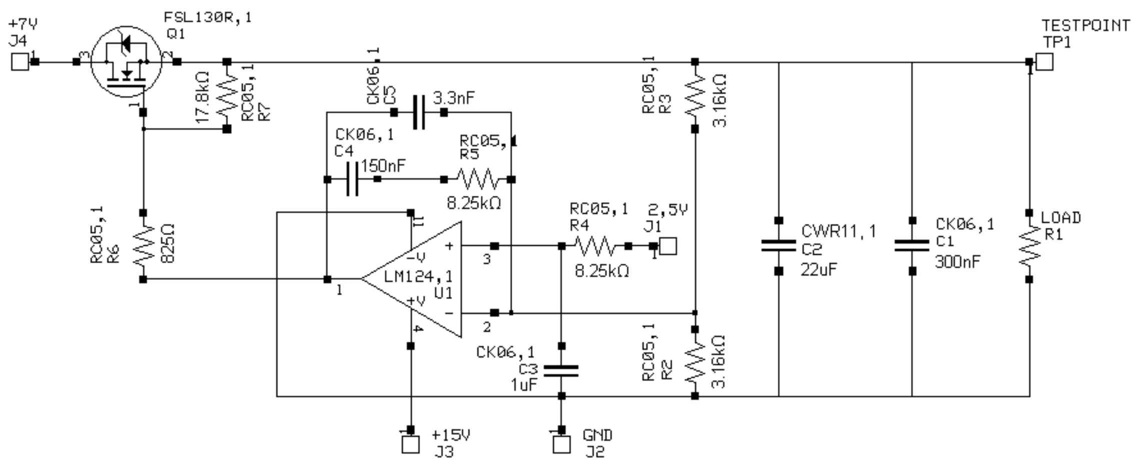


Fig 6.1.1 Schematic drawing of the 5-volt regulator test set-up. The "Load R1" is 115 ohm.

6.2 Results of Using LM124NS In the Application

In this 5-Volt regulator application set-up a cross-section for LET = 30 MeV/mg/cm^2 of 4E-4 cm^2 was determined. The Op-Amp was here operated in linear mode and only positive SET's were observed. . This cross section is higher than for the device tested in comparator mode (see Fig 5.1.1). Linear mode has not been tested for the Op-Amp itself. Apart from the differences in test modes, different oscilloscope trigger levels could also influence the results.

Pulse amplitudes greater than 0.1 Volt have pulse duration between 50 to 80 µs, which correspond to the discharge time of the capacitor C2 in Fig 6.1.1, see also Figs 6.2.1 and 6.2.2. The maximum pulse width is about 240 µs, which correspond to the discharge time of the capacitor from 5.5 to 5 Volt. A P-Spice simulation of this design shown in Fig 6.2.3, give a similar result to the observed pulses.

Negative pulses can not be expected since the RC time is about 2.5 ms and a SET is no longer than 10 ns (see figure 6.1.1, C2 = 22 µF and R1 = 115 ?).

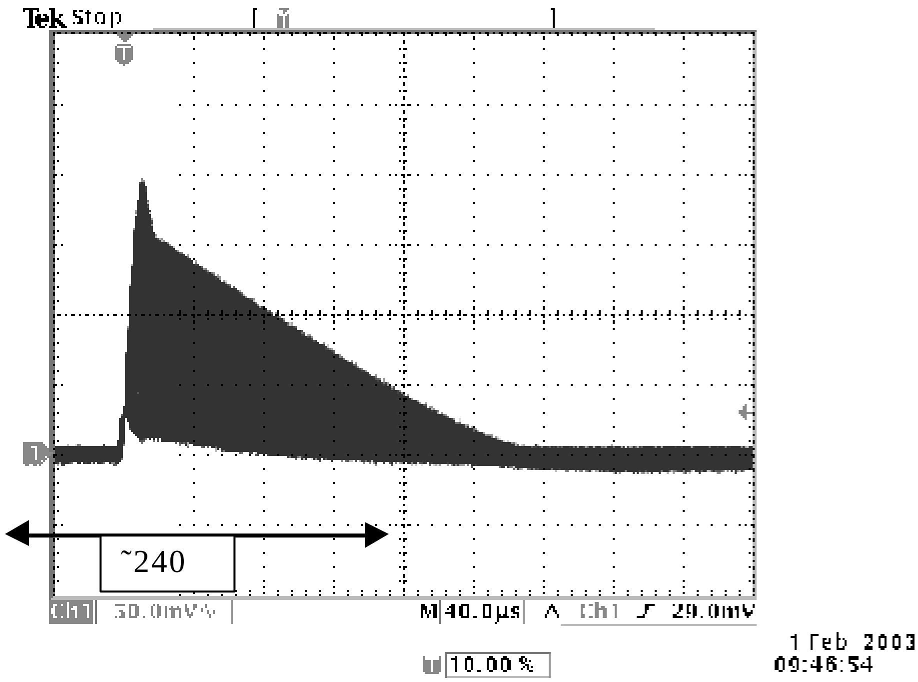


Fig 6.2.1 Oscilloscope picture showing positive going SET pulses measured at Testpoint TP1 in Fig 6.1.1

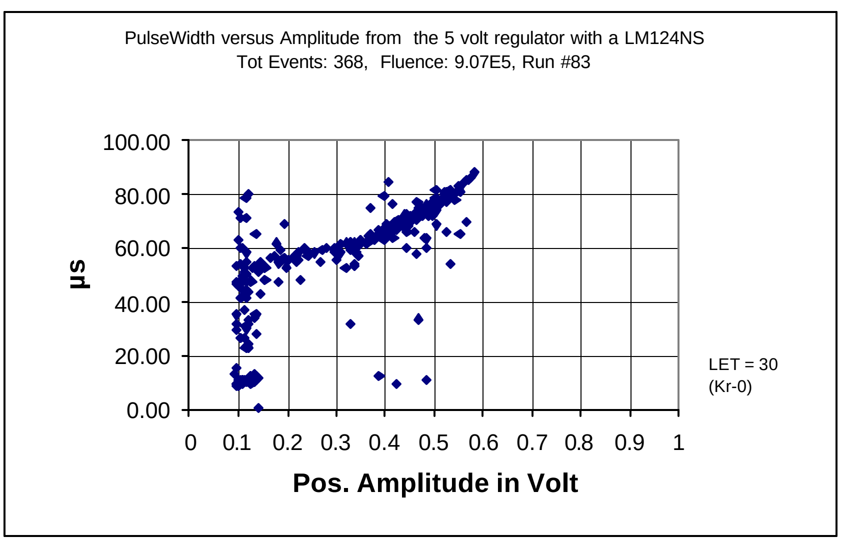


Fig 6.2.2 Scatter diagram showing SET pulse widths in ms versus amplitude in Volt.

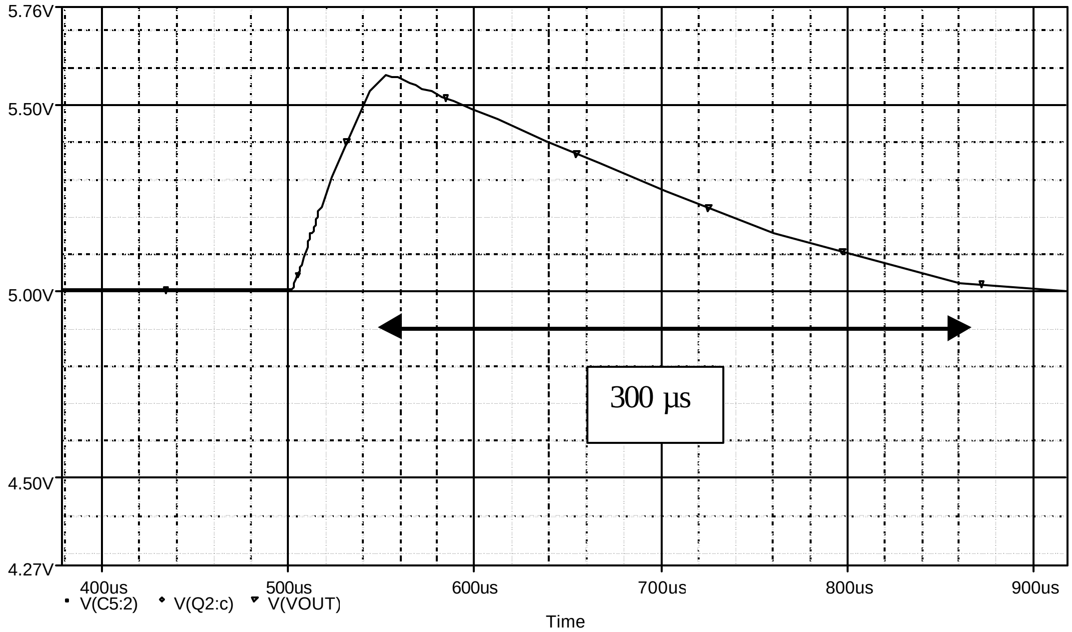


Fig. 6.2.3 Result from a P-Spice simulation of the 5-Volt regulator.

7. CONCLUSION

Single Event Transients induced by heavy ions have been measured for four different Operational Amplifiers operating in “comparator mode”. The Op-Amps were LM124 from National Semiconductor and Texas Instrument, RH1014 from Linear technology and OP27 from Analog Devices.
The two LM124 devices show about the same SET behaviour with SET reponse of about 40 µs as maximum duration and a cross section of about 4E-5 cm^2 starting at a LET of about 20 MeV/mg/cm^2.
The radiation hard Op-Amp (RH1014) show about the same cross section, but the LET threshold is higher. However, for higher LET value this device indicates to respond with very long SET pulses, up to 300 µs long.

The OP27 is a fast Op-Amp with corresponding very fast SET pulses. No SET pulses above 0.6 µs were recorded for any LET value up to LET=59 MeV/mg/cm^2.

All devices have been tested in comparator mode. No differences in cross section were detectable between the two delta-input voltages. However for RH1014, transients were detected with about 30% larger width for the low delta input voltage (?Vin = 0.2V) compared to the high delta input voltage (?Vin = 5V).

LM124 from National Semiconductor has been investigated by Poivey et. al. [1] and Label et. al. [2] for SET’s. This reports show similar results as presented in this investigation concerning the cross section and pulse duration.

For radiation design analysis the normally used pulse widths for Op-Amps are in the range 15-40 µs. The observation of the very long pulses from RH1014, indicate that pulse widths must be verified for each individual Op-Amp to make safe design analysis.

References:

1 C. Poivey et.al. “ Single Event Transients in LM124 operational amplifier Heavy ion test report”, NASA publications, 2001

2 K. Label et. al. “Single Event Transients in LM124 operational amplifier Laser test report”, NASA publications.

8. Appendix

RUN#	ION	LET	FLUENCE	DEVICE	?V	Neg. pulse
13	Kr	29.4	2.00E+06	LM124TI	5 V	105
14	Kr	58.8	1.34E+06	LM124TI	5 V	111
15	Kr	43.9	1.62E+06	LM124TI	5 V	109
16	Kr	58.8	1.21E+06	RH1014	5 V	117
17	Kr	43.9	2.97E+06	RH1014	5 V	101
18	Kr	29.4	7.28E+06	RH1014	5 V	102
19	Kr	58.8	1.76E+06	LM124NS	5 V	104
20	Kr	43.9	1.90E+06	LM124NS	5 V	102
21	Kr	29.4	3.51E+06	LM124NS	5 V	122
22	Kr	58.8	2.80E+06	LM124NS33	5 V	0
23	Kr	58.8	6.09E+06	OP27	5 V	10
24	Kr	58.8	3.81E+06	OP27	0.2 V	12
25	Kr	58.8	2.31E+06	LM124NS33	0.2 V	0
26	Kr	58.8	1.65E+06	LM124NS	0.2 V	101
27	Kr	43.9	2.30E+06	LM124NS	0.2 V	103
28	Kr	29.4	3.33E+06	LM124NS	0.2 V	106
29	Kr	29.4	8.54E+06	RH1014	0.2 V	104
30	Kr	43.9	3.55E+06	RH1014	0.2 V	102
31	Kr	58.8	1.60E+06	RH1014	0.2 V	109
32	Kr	58.8	1.39E+06	LM124TI	0.2 V	104
33	Kr	43.9	1.66E+06	LM124TI	0.2 V	114
34	Kr	29.4	5.87E+06	LM124TI	0.2 V	272
35	Fe	18.0	2.99E+06	LM124TI	0.2 V	112
36	Fe	29.2	1.81E+06	LM124TI	0.2 V	118
37	Fe	29.2	4.14E+06	RH1014	0.2 V	50
38	Fe	18.0	5.60E+06	RH1014	0.2 V	0
39	Fe	23.5	2.98E+06	RH1014	0.2 V	10
40	Fe	18.0	3.27E+06	LM124NS	0.2 V	113
41	Fe	23.5	1.30E+06	LM124NS	0.2 V	62
42	Fe	29.2	1.68E+06	LM124NS	0.2 V	71
43	Fe	29.2	1.50E+06	LM124NS	5 V	62
44	Fe	18.0	1.67E+06	LM124NS	5 V	57
45	Fe	18.0	1.91E+06	LM124NS	5 V	58
46	Fe	18.0	4.12E+06	RH1014	5 V	0
47	Fe	23.5	2.70E+06	RH1014	5 V	14
48	Fe	29.2	4.06E+06	RH1014	5 V	49
49	Fe	29.2	1.03E+06	LM124TI	5 V	82
50	Fe	23.5	1.29E+06	LM124TI	5 V	89
51	Fe	18.0	2.23E+06	LM124TI	5 V	108
53	Si	14.2	2.13E+06	LM124TI	5 V	55
54	Si	10.6	4.18E+06	LM124TI	5 V	0
55	Si	14.2	3.01E+06	LM124NS	5 V	2
56	Si	14.2	6.14E+06	LM124NS	5 V	1
57	Si	14.2	6.04E+06	LM124NS	0.2 V	1
58	Si	14.2	2.07E+06	LM124TI	0.2 V	57
59	Si	10.6	5.19E+06	LM124TI	0.2 V	0
83	Kr	30.3	9.07E+05	5V reg.		368 (pos.)
87	Kr	39.6	3.60E+05	8.8V reg.		120 (neg.)
89	Kr	30.3	1.19E+05	8.8V reg.		36 (neg.)