

NEPP/ERC

**APPLICATION NOTES FOR
ANALOG LINEAR DEVICES**

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1 INTRODUCTION

Single Event Transients (SETs) or analog Single Events Upsets (SEUs) in linear devices were first identified following an in flight anomaly in TOPEX POSEIDON [1]. Since that event, SETs have been identified as the cause of several anomalies on multiple satellites including SOHO, CASSINI, MAP, TDRSS, and TERRA.

A SET is caused by the generation of charge by a single particle: proton or heavy ion. It consists of a transient pulse generated within the device that produces an effect at the device output. That effect can be the same voltage transient or an amplified version of that voltage transient.

A transient pulse from a linear device can propagate and produce effects that could cause failures in flight hardware and systems. False information potentially generated by an analog SEU in flight hardware should be taken into account and the impact at the subsystem/system level analyzed. It is especially important if the function being performed is deemed critical (equipment RESET, shutdown, etc...).

The study of and hardening to such events is a three-step process. *First, a description of the consequences of analog SEU at equipment level must be done. Secondly, an analysis of the SET impact at the system level and identification of critical events and acceptable rates needs to be developed. Finally, any required mitigation of critical events at system/subsystem or equipment level must be implemented.*

To do this criticality analysis it is very important to get accurate transient characteristics (voltage amplitude, pulse width) information.

Variations in the input and bias conditions utilized are known to dramatically change the event rate and generated transient characteristics (peak heights and widths). This implies that either the radiation test data must be taken over a very large parameters space or application-specific testing must be done for each application of each device type.

Different Radiation Hardness methodologies have been proposed [2-4]. They all propose laser testing to reduce the amount of heavy ion testing to check. Some [2] propose worst-case models in absence of data. Based on our experience we recommend to always taking data.

The ideal case would be to have mitigation designed into the system at the beginning of the design, and when the radiation data become available, no design change would be required.

This is the objective of this document to provide designers information about transient characteristics in the main types of analog devices. Even on parts for which data are neither available nor applicable, this information will give clues to reduce the mitigation effort later in the design stage.

2 ANALYSIS OF THE IMPACT OF A TRANSIENT IN A DESIGN

The general rules described in the NASA criticality analysis document [7] are applicable for SET in linear devices.

The failure definition for SET shall be in terms of an output voltage amplitude, ΔV_f and pulse width, PW_f . A failure criterion is first established for the application circuit and flowed down to each linear circuit in the system application. One approach that has been shown to be viable for this analysis is to use a circuit analysis code such as SPICE to represent the application circuit and use SPICE macro-models to represent the linear circuits in the application circuit [8, 9].

The values of ΔV_f and PW_f for each linear circuit are found by inserting a voltage pulse at the output of the linear circuit macro-model and varying the pulse height and width until the application circuit failure criterion is met at the out put of the application circuit.

An example of an application circuit is shown in Figure 1 [9]. This circuit is used to monitor the power distribution in a satellite. The LM124 and OP27-1 are used for current limiting and OP27-2 is used as a current sensor.

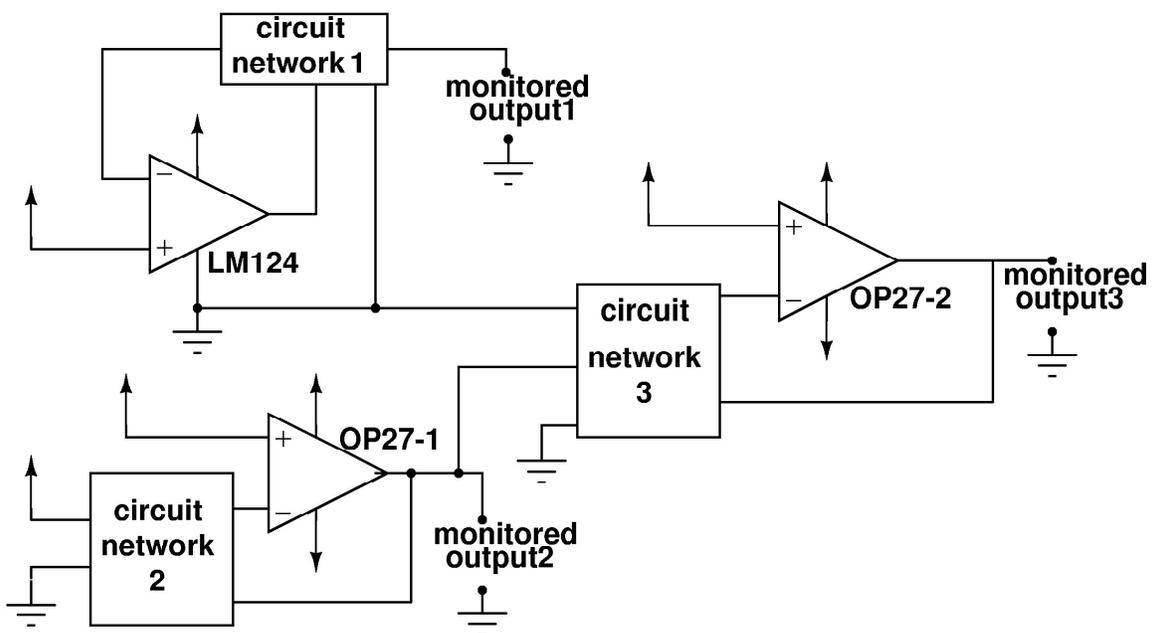


Fig 1: example of application circuit

The System engineer has determined that this application circuit will cause a system failure if a transient at output 3 exceeds 1.8V for more than 6 μs . This requirement is then flowed down to the three linear circuits in the application circuit. Since the output of OP27-2 is the output of the application circuit the failure criterion for OP27-2 is the same as the failure criterion of the application circuit. The analysis for the LM124 and the OP27-1, using macro-models for the linear circuits not struck by the heavy ion pulse, and a validated SPICE micro-model to generate the SET, determined that the failure criterion for these linear circuits is an SET that exceeds 1.25V for 6 μs . Hence, the worst case ΔV_f and PW_f for both the LM124 and OP27 for this application is 1.25V for 6 μs . [When the micro-model is not available, the same analysis can be done by injecting transients perturbations at the output of the device supposed to be struck by the ion.](#)

Once a failure definition has been established, it is also important to define, as described in the criticality analysis document [7] a criticality class and then an acceptable error rate.

3 MITIGATION TECHNIQUES

There are as many ways to mitigate SETs as there are ways to utilize linear devices. The most simplistic, and often the most effective, is through filtering the output of the linear devices. In some applications, filtering may not be an option and other techniques will have to be employed. In some devices, their susceptibility to SETs and the transient characteristics are a strong function of the input and bias conditions. Therefore, a very simple way to mitigate transients in these devices is have input and biasing scheme that are less susceptible, if possible. Next, as with other transient events, a very powerful way to avoid transients is to use a synchronous design. Finally, some other mitigation methods available are voting, over-sampling, and/or software.

4 DEVICE DATA

4.1 Introduction

The SET response of an analog circuit is usually presented in terms of an SET cross section vs. LET for a given set of operating conditions. The cross section is normally calculated from the total number of SETs divided by the effective particle fluence. An SET is defined as any output transient exceeding a threshold change in output voltage for a specified time. While the device error cross section for a digital circuit is usually well defined, for an analog part SET data presented in this form is of little value in establishing an ASET error rate in space. The first reason is that the SET response may be sensitive to the supply voltage, the input voltage and the output load. For example, the voltage comparators SET response is usually a strong function of the differential input voltage, δV_i , with greater sensitivity for smaller values of δV_i . Therefore, as mentioned before, data need to be taken for the specific application bias condition. The second reason is that many, or even all, of the SETs may not cause a failure of the application circuit. What is required to determine an error rate for a given application is the cross section vs. LET for SETs that meet or exceed the failure criteria for the application. Figure 2 shows an example of the variation of the sensitivity in function of the transient amplitude. We can see that the largest transients represent only a small fraction of the total number of transients.

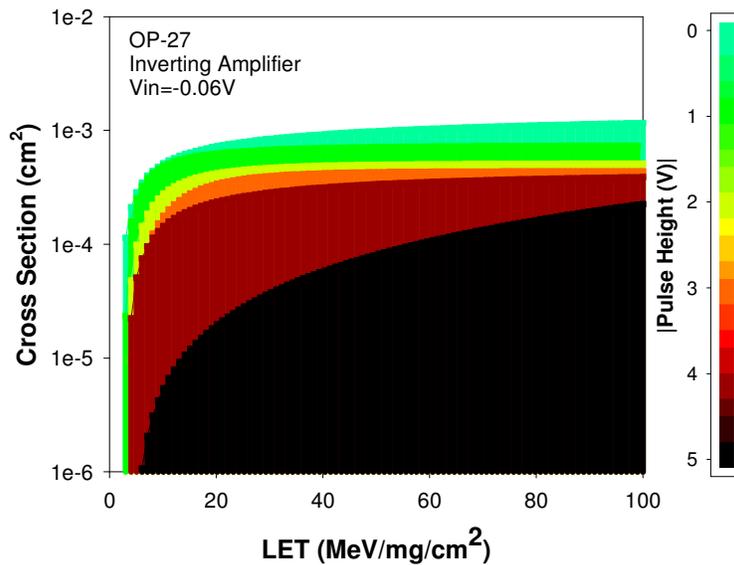


Fig 2: Cross section curves of the OP27 in an inverting amplifier configuration with an input voltage of -0.06V for different SET amplitudes [10].

In addition to the cross section information, it is important to present information on the SET characteristics. It has been shown [11, 12, 13] that the most effective way of presenting transients characteristics is the transient peak voltage amplitude δV versus and full width at half maximum (FWHM) pulse-width plot. An example of these plots is shown in Figure 3.

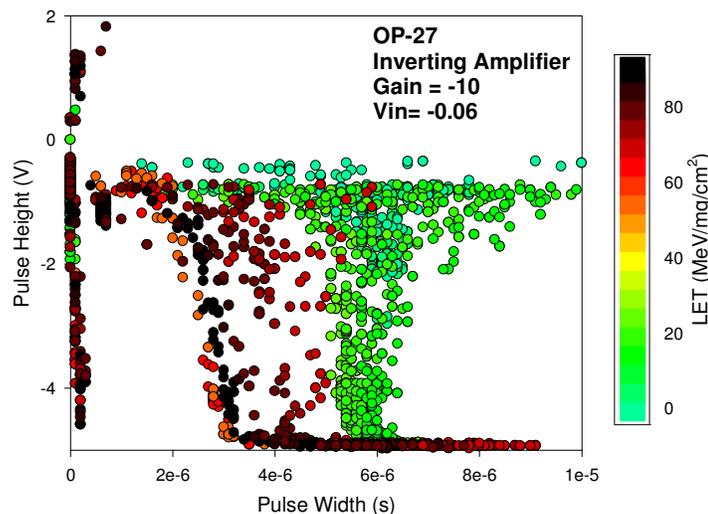


Fig 3: δV versus FWHM plot for the OP27 used as an inverting amplifier [10]

When this information is available for a bias condition bounding the actual application condition and a failure criterion is defined, the actual cross section of fail pulses may be defined. Then, a failure rate may be calculated. An example of the presentation of the data in a format that

can be used to assess the ASET error rate for the application circuit example above is given in Figure 4.

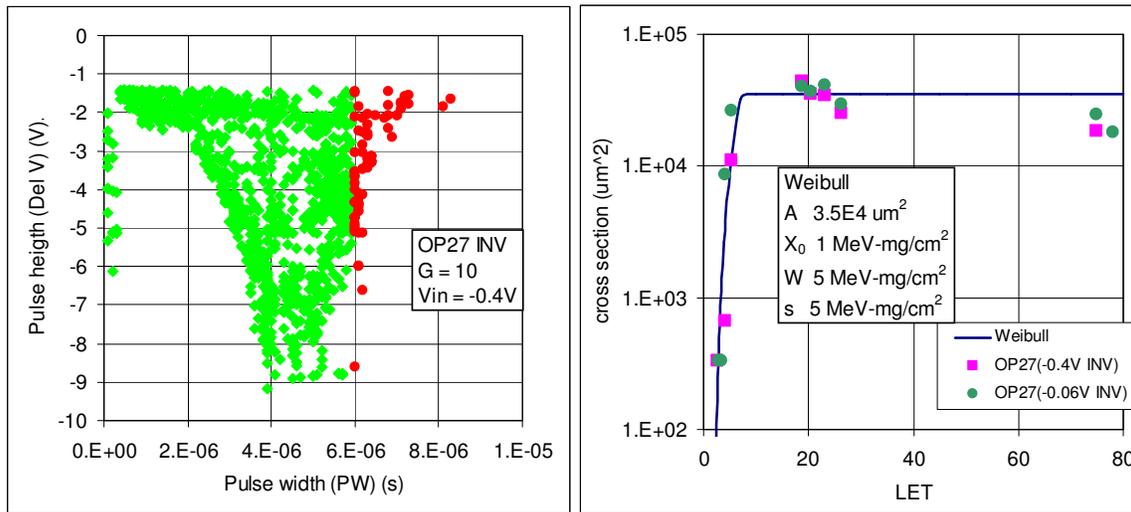


Figure 4: Example of SET analysis of OP27 for inverting gain of 10 configuration with $V_{in} = -0.4V$. The left side shows pulse height vs. pulse width with SETs in red exceeding the failure criteria of 1.25V, 6 μs . The right side shows the cross section of SET fail pulses vs. LET with Weibull fit for two values of V_{in} . [3]

It is not possible to present plots like those of Figure 4 for all possible application and failure criteria. Therefore, for each case, even when valid data are available; it will be necessary to get back to the data to define a cross section corresponding to the actual application criteria. What will be presented in this document is the total cross section, and information about transient characteristics with Pulse height versus Pulse width plots when available.

Most of the data available in the literature is heavy ion data.. As the heavy ion Linear Energy Transfer (LET) threshold (i.e., a measure of the device's susceptibility to these effects) is generally very low, proton sensitivity is expected. Only a few sets of proton data are available [5, 6], but available proton data confirms this sensitivity. However, proton data on 139 type voltage comparators [5, 6] show that the devices are only sensitive for very small input differential voltage bias conditions, around 10 mV. One reason for this is the long collection depths of these devices [16, 49]. SETs are observed on operational amplifiers [6] but are generally of smaller amplitude than the ones caused by heavy ions. The number of proton induced SET may be significant. For example, the MPTB analog experiment results show that the majority of SETs observed on the LM124 are proton induced SETs [50].

4.2 Voltage Comparators

4.2.1 Introduction

The SET data available in the literature on voltage comparators is listed in Table 1. The table also gives the worst-case test results observed. The effect of a SET in a voltage comparator is a transient pulse at the device output that can have characteristics of a rail-to-rail change of state of the comparator output with duration of a few microseconds. **In general, it has been observed that the lower the comparator differential input voltage is the higher the device sensitivity.**

Table 1: List of available data on voltage comparators

Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /device unless other wise specified
LM139	NSC	[14, 15, 6, 5]	LET _{th} ~2, σ ~5x10 ⁻⁴ (100 mV δ V _i , >500mV transients)
PM139	AD	[6, 16, 5]	LET _{th} ~4, σ ~6x10 ⁻⁴ (200 mV δ V _i , >500mV transients)
HS139RH	Intersil	[14, 15]	LET _{th} ~3, σ ~5x10 ⁻⁴ (100 mV δ V _i , >500mV transients)
LM339	STM	[17]	LET _{th} <2, σ ~1.2x10 ⁻³ (30 mV δ V _i , >2V transients)
LM119	NSC	[18, 19, 20]	LET _{th} ~3, σ ~1.2x10 ⁻³ (-5V δ V _i , >300mV transients)
RH119	LTC	[21]	LET _{th} <6, σ ~3.3x10 ⁻⁴ (580 mV δ V _i , >2 V transients)
LM111	NSC	[12, 22, 20, 5, 23]	LET _{th} <3 σ ~1x10 ⁻³ (50 mV δ V _i , >100mV transients)
LM111	Motorola	[24]	LET _{th} ~2, σ =3x10 ⁻⁴ (100 mV δ V _i , >2.4V transients)
LM193	TI	[25]	LET _{th} ~2, σ =1.5x10 ⁻³ (100 mV δ V _i , >500 mV transients)
AD9696	AD	[20]	LET _{th} <5, σ =2x10 ⁻⁵ (50 mV δ V _i , >100 mV transients)
LP365	NSC	[16]	LET _{th} <4, σ =1x10 ⁻³ (10 mV δ V _i , >500 mV transients)

4.2.2 LM139, National Semiconductors

Fig 5 shows typical LM139 transients [14]. They all have the same shape with a sharp increase and then an exponential decrease.

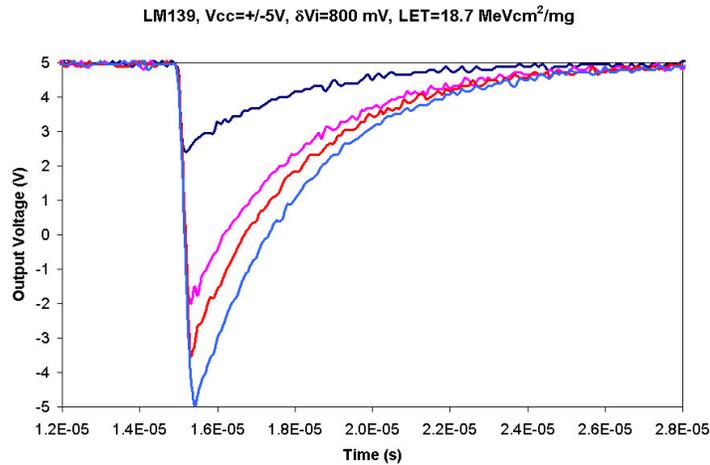


Fig 5: typical LM139 SETs

Fig 6 shows the SET peak amplitude versus FWHM plot for an input differential voltage δV_i of 50 mV for three irradiation runs at different LET. We can see that as soon as the LET is higher than 3 MeVcm²/mg, most of them reach their maximum amplitude. At high LET most transients are saturated; once they reach the power supply voltage rail they stay at the rail for a short period of time before starting the decrease.

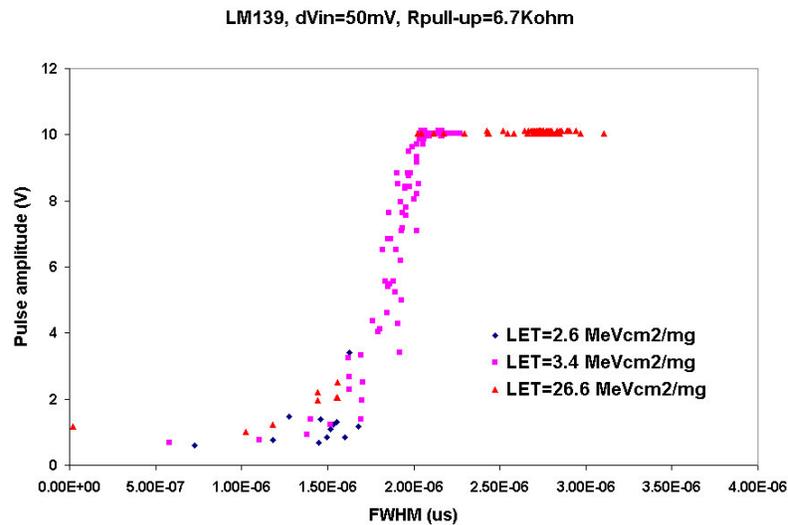


Fig 6: SET peak amplitude versus FWHM for $\delta V_i=50$ mV

Fig 7 shows a saturated transient waveform.

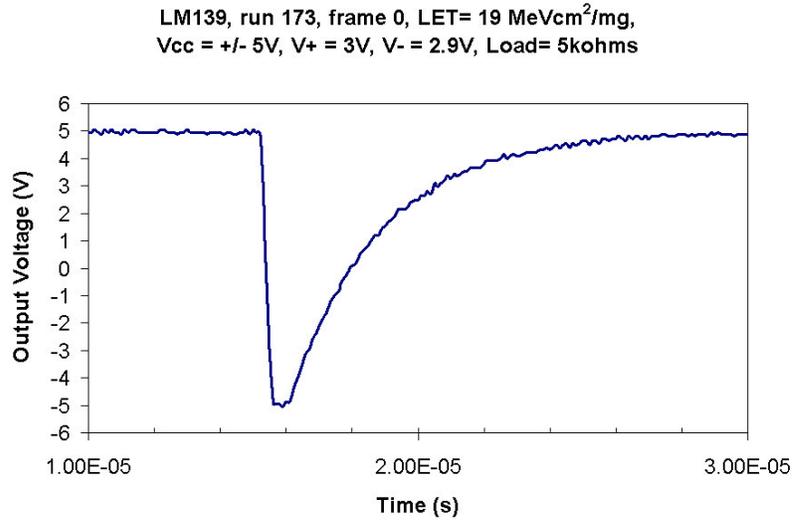


Fig 7: Saturated SET waveform

Figs 8 and 9 show the SET peak amplitude versus FWHM for an input differential voltage δV_i of 100 mV and 1 V respectively. We can see that the input differential voltage does not change the waveform. However, for the higher value of δV_i , fewer transients reach the maximum amplitude

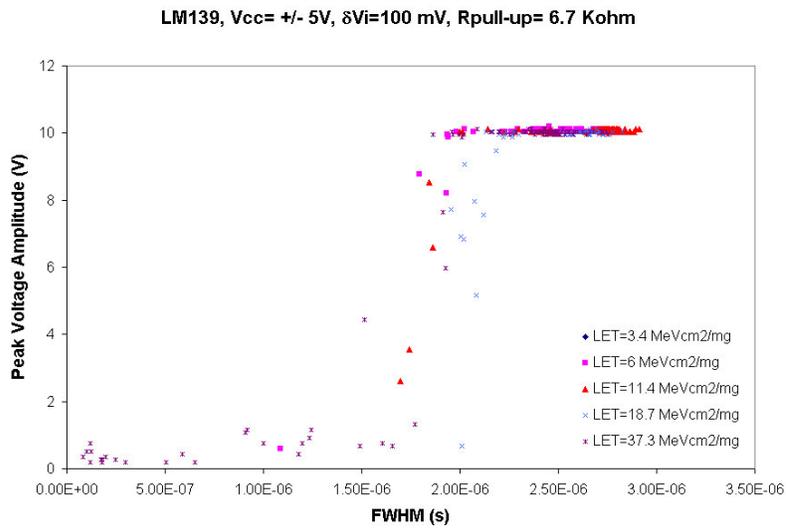


Fig 8: SET peak amplitude versus FWHM for $\delta V_i=100$ mV

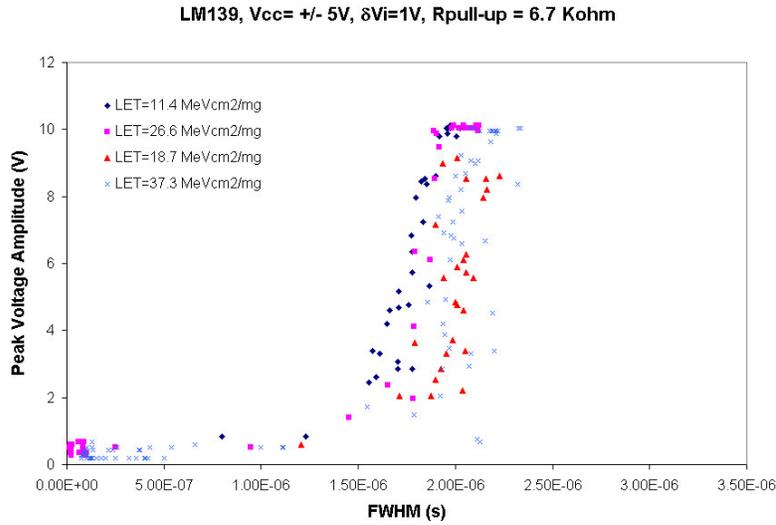


Fig 9: SET peak amplitude versus FWHM for $\delta V_i=1 V$

The input differential voltage has an effect on the device sensitivity. Fig 10 shows the LM139 SET cross-section curves for different values of δV_i . Higher δV_i is, lower the device sensitivity is.

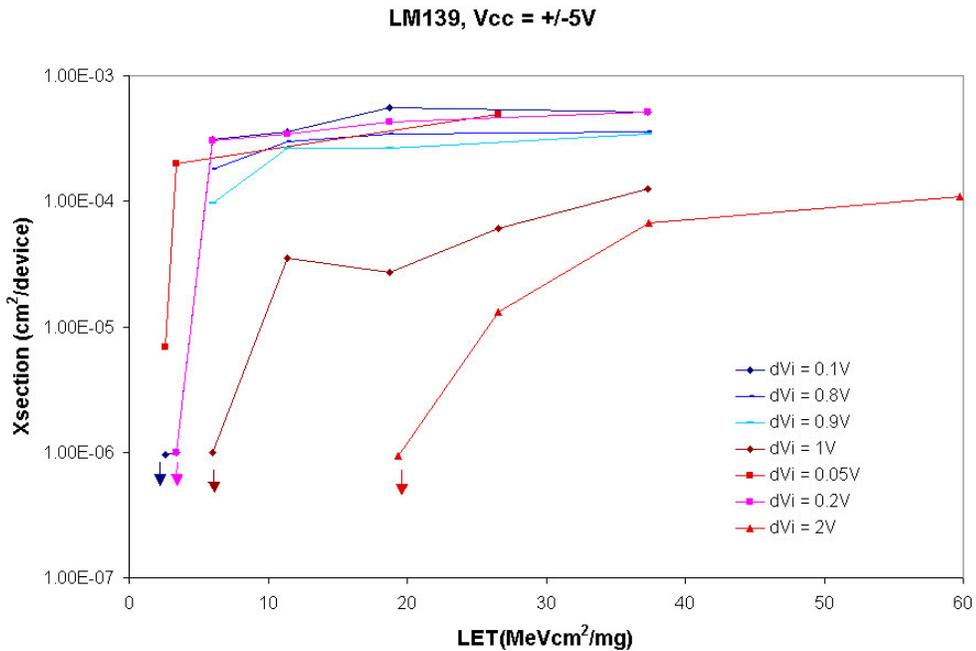


Fig 10: LM139 SET cross-section curves

The LM139 voltage comparator has an open collector output that is connected to a pull-up resistor. The value of the pull-up resistor does not impact the device sensitivity but has an effect on the transient waveform as shown in Fig 11.

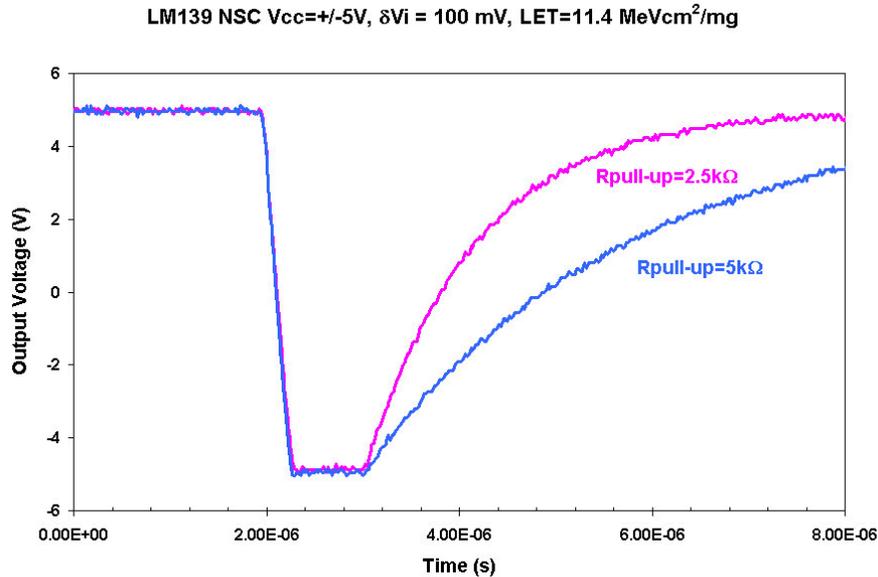


Fig 11: Transient waveforms obtained for two different values of the pull-up resistor

When the nominal voltage comparator output state is low, the LM139 is also sensitive to SET. However, the sensitivity is lower and the transients are significantly smaller. The SET never reach the supply voltage rails. Maximum SET amplitude measured is 2V.

The low LET threshold, as least for low δV_i ($< 1V$) suggest sensitivity to proton induced SET as well. Nichols [5] shows that the LM139 is sensitive to proton induced SET but only for very low δV_i (around 10 mV). The proton SET cross section are very small. The maximum measured cross section measured with 200 MeV protons is about $3E-10 \text{ cm}^2$ for a δV_i of 12.5 mV. Rail to rail transients were observed, but the transient duration is much shorter than the one obtained with heavy ions. A typical transient width is about 200 ns. [When test conditions approach a threshold appropriate to the \$\delta V_i\$ and proton energy, most transients have a small amplitude.](#)

4.2.3 PM139, Analog Devices

The PM139 from Analog Devices has a similar design than the LM139 one's [5, 16]. Test data show that they have a very similar behavior when exposed to heavy ions. The transients have the same waveform on both devices, and the devices cross section are very close as shown in Fig 12.

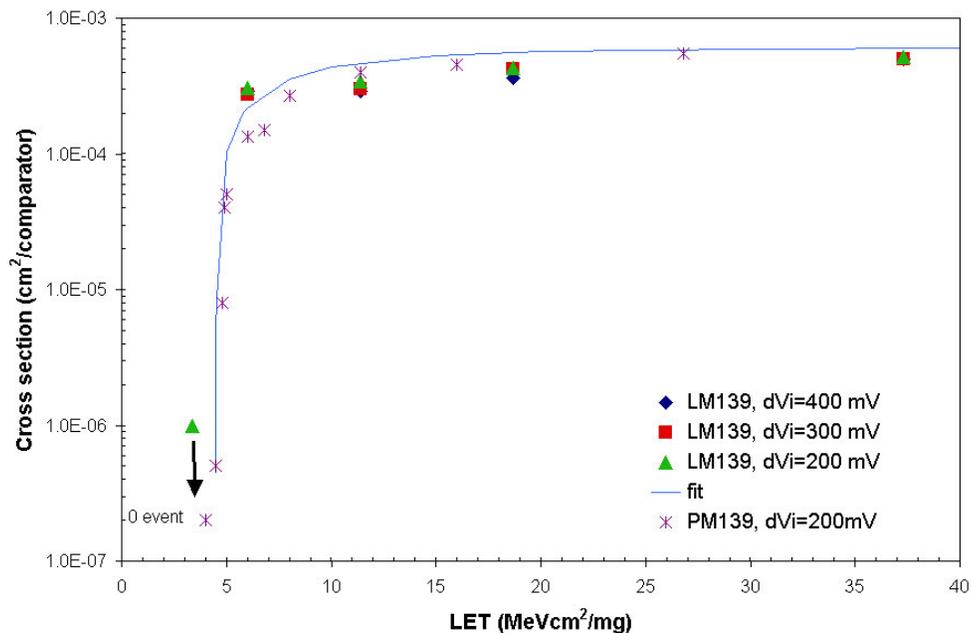


Fig 12: SET cross section curves of LM139 NSC and PM139 AD.
 (Data for PM139 AD is coming from [16])

The PM139 voltage comparator did not produce any transient when exposed to Cf252, even when δv_i was reduced to 10 mV [16]. It demonstrates that a charge collection depth well beyond the range of fission fragments is necessary to produce transients in these devices. The PM139, as well as the LM139, is fabricated on lightly doped substrates that not only have long charge collection depths, but also use collector wells that are approximately 10 μm deep, along with a buried layer that extends even further into the substrate. This particular fabrication technology requires ions with far more range than typical digital circuits with more compact vertical structure. The PM139 exhibits the same proton sensitivity as the LM139 [5, 6]

4.2.4 HS139RH, Intersil

The HS139 voltage comparator from Intersil also has a similar design than those of LM139 and PM139. The behavior when exposed to heavy ions is similar. Data [14, 15] show that SET waveforms are the same. However, unlike the LM139, the SET cross sections for the HS139 do not have such a strong dependence on δv_i . Fig 13 shows the HS139 the SET cross sections for different values of δv_i . We can see in Fig 13 that cross sections measured at the maximum LET for the different δv_i are within a factor 2. The worst case saturation cross section of Intersil HS139 is similar to the one of National LM139. But, the worst-case threshold LET value for LM139 is substantially smaller than that for HS139. HS139 devices are less sensitive to SET than LM139 devices for low δv_i (<1V). But for large δv_i (>1V), HS139 devices become more sensitive than LM139 devices.

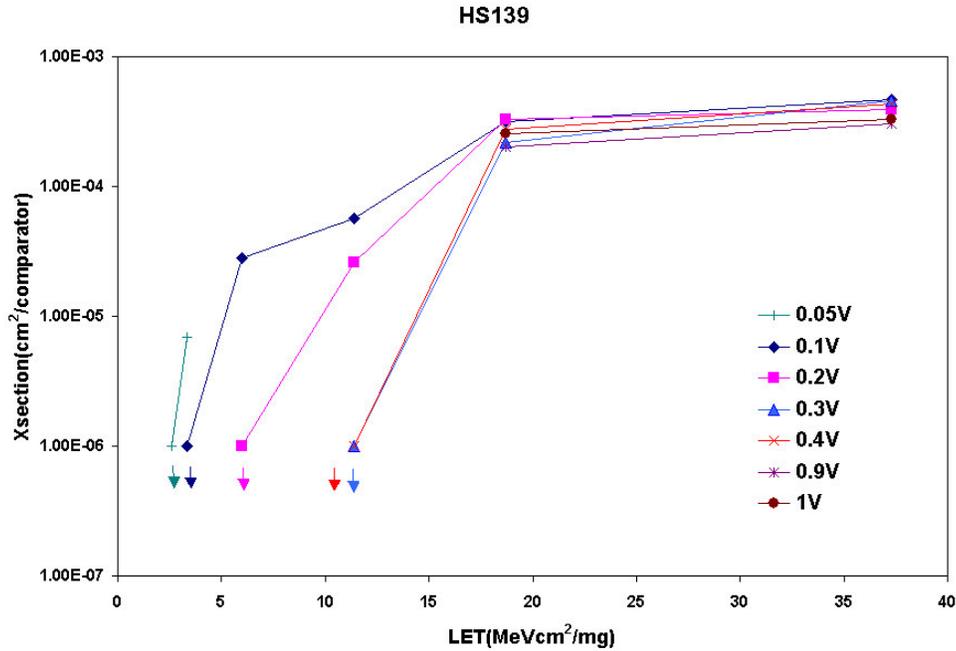


Fig 13: HS139 SET cross section for different values of δV_i [14]

4.2.5 LM339, STM

This device has the same sensitivity the other 139 voltage comparators. The transients have a similar waveform then the other 139 voltage comparators as well [17]. The LM139 from STM has a slightly lower sensitivity to protons than the other 139 devices from NSC and AD [6]

4.2.6 LM119, NSC

LM119 is a fast voltage comparator that also has an open collector output. Fig 14 shows a typical transient when the δV_i is positive. The transients are very similar to those observed with the 139 type voltage comparators. At maximum amplitude the transient reach the ground rail very quickly and then decreases exponentially, corresponding to the charge of the output capacitor through the pull-up resistor when the output transistor is turned off again. Fig 15 shows SET amplitude versus FWMH plot for $\delta V_i=2.5V$. We can see that at the lower LET of 11.4 MeVcm²/mg no transient reach the maximum amplitude. At the higher LET values most of the SET reach the maximum amplitude. Maximum transient FWMH is about 600 ns.

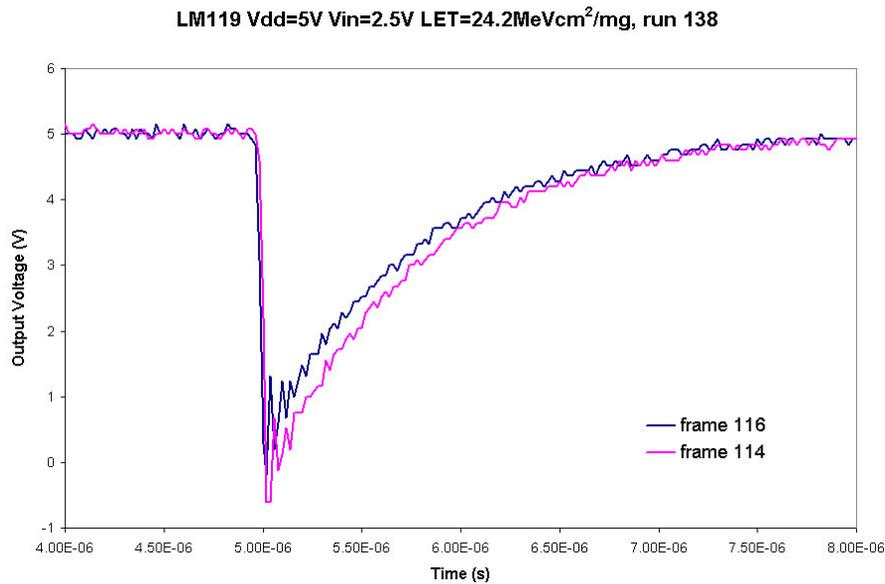


Fig 14: Typical transient with the device output connected to 5V through a 1.7 K Ω pull-up resistor.

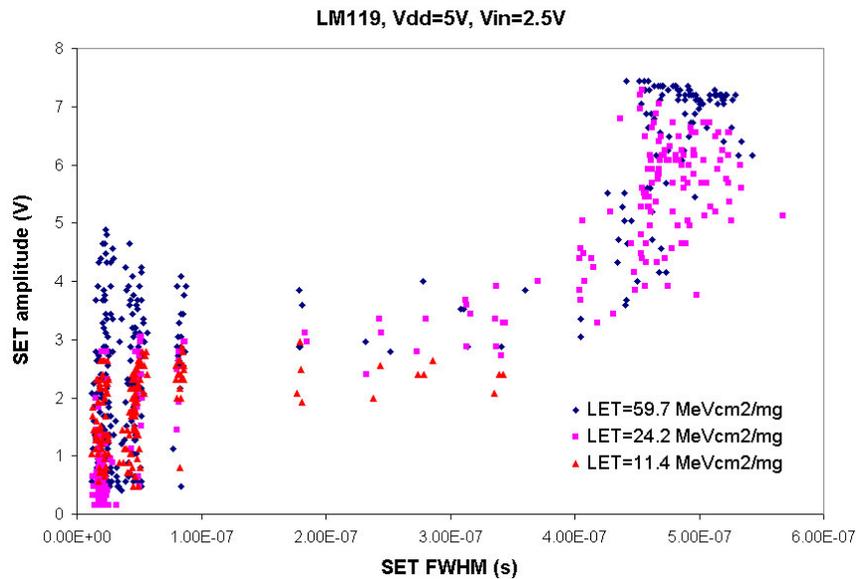


Fig 15: SET amplitude versus FWHM for a positive δV_i , Vdd= \pm 5V, Output connected to 5V through a 1.7 K Ω pull-up resistor.

The dependency of LM119 sensitivity to δV_i is completely different to the one of the 139 type voltage comparators. Fig 16 shows the SET cross section curve for different values of δV_i . We can see that the cross section for negative differential input voltages is one order of magnitude larger than for positive differential input voltages. Except the sign of δV_i , we do not see an effect of the value of δV_i on device SET sensitivity.

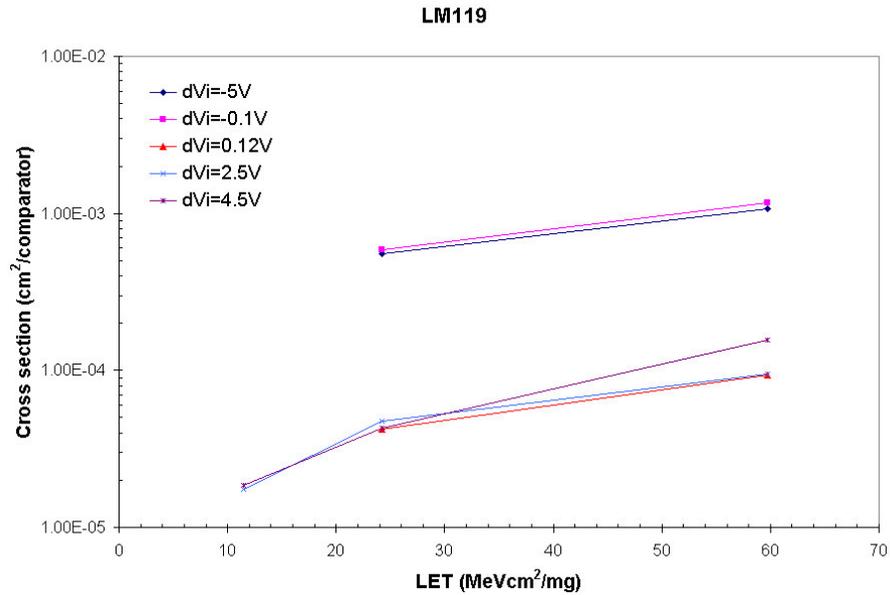


Fig 16: SET cross section curve as a function of ion LET for the LM119 voltage comparator for positive and negative input differential input voltages [18]

Fig 17 shows a typical transient when δV_i is negative. It starts with an exponential, corresponding to the charge of the output capacitor through the pull-up resistor, and very fast decrease, corresponding to the discharge of the output capacitor when the output transistor turns on again. Because of the time needed to charge the output capacitor, the largest transients do not reach the output power supply rail. However, some of them are large enough to see a change of the comparator state for about 100 ns.

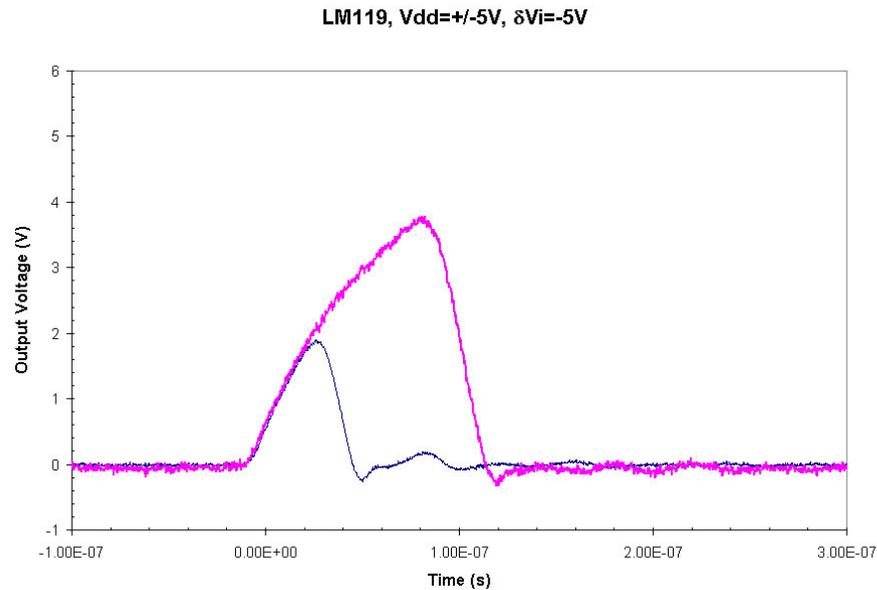


Fig 17: LM119 Typical transients waveforms when δV_i is negative [19]

4.2.7 RH119

Available test data [21] show that RH119 and LM119 have very similar transient waveforms. The SET sensitivity is also similar. However, we do not see an effect of the sign of δV_i on the RH119 SET sensitivity. Fig 18 shows the SET cross section curves for different values of δV_i . It is difficult to see a clear effect of δV_i on the device SET sensitivity.

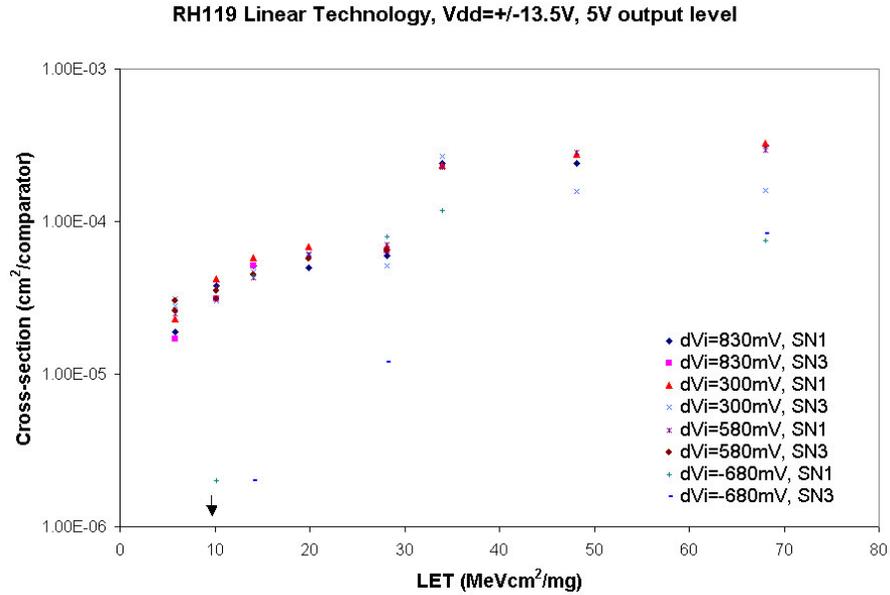


Fig 18: RH119 SET cross section curve for different δV_i values [21]

4.2.8 LM111, NSC

The LM111 shows the same transient waveforms than the other voltage comparators [12, 22]. Fig 19 shows a typical transient when the nominal output voltage is high. Like for the LM139, the LM111 SET sensitivity depends strongly on the input differential voltage [20]. Higher δV_i is, lower SET sensitivity is.

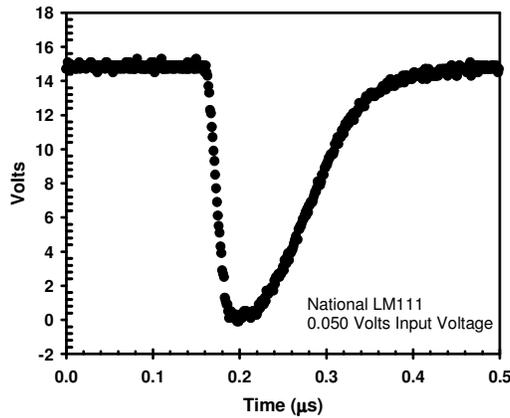


Fig 19: Typical negative going SET waveform,
 $V_{cc} = \pm 15V$, $R_{pull-up} = 2.2 k\Omega$

4.2.9 LM111, MOTOROLA

The waveforms of the LM111 Motorola transients are similar to the LM111 NSC ones. The sensitivity is similar as well [24].

4.2.10 LM193, TI

Fig 20 shows the LM193 SET cross-section curves [25]. For the range of δV_i investigated in these experiments, from $-0.5V$ to $+0.5V$, we do not see an effect of δV_i on the device SET sensitivity. However, all the δV_i investigated are small. For larger δV_i we expect lower sensitivity as for the LM139 because the LM193 and the LM139 have very similar electrical designs.

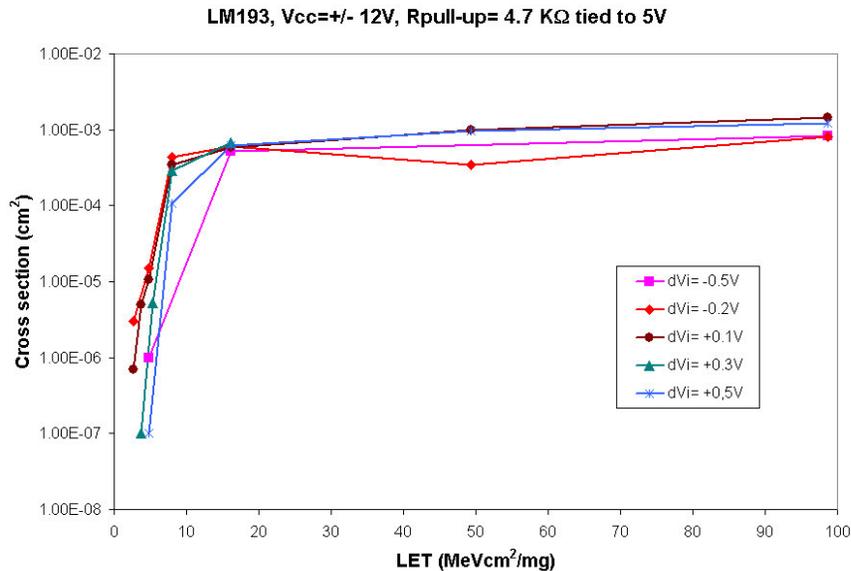


Fig 20: LM193 SET cross-section curves

Most of the transients reach the maximum amplitude. Unlike the LM139, the negative going transients, when the comparator output state is high, and the positive going transients, when the comparator output state is low, have the same shape and characteristics. At low LET, around $5.3 \text{ MeVcm}^2/\text{mg}$, the maximum duration is about 500 ns . At the highest LET of $98 \text{ MeVcm}^2/\text{mg}$, the maximum duration is about $1.4 \text{ }\mu\text{s}$. Figs 21 and 22 show large negative going and positive going transients respectively.

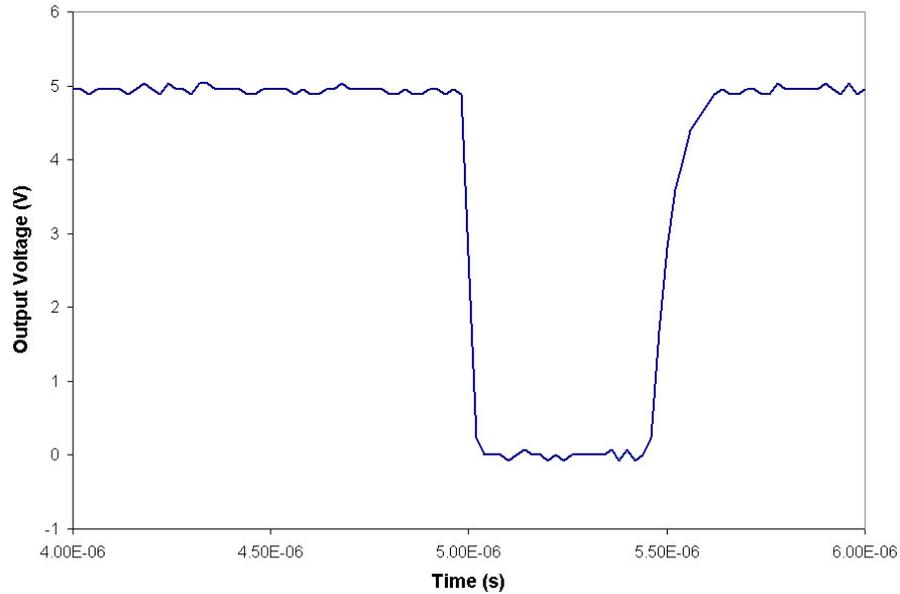


Fig 21: large negative going transient

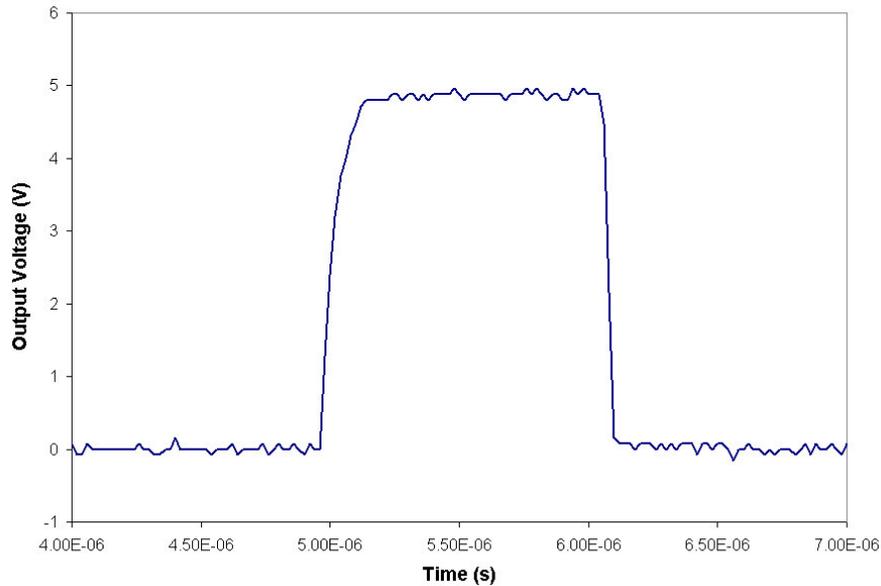


Fig 22: large positive going transient

4.2.11 AD9696, AD

We do not have any information on the SET waveform. The SET LET threshold does not change appreciably with δV_i . However, the saturation cross-sections tend to be somewhat larger when δV_i is smaller than a few hundred millivolts [20].

4.2.12 LP365, NSC

Test results show a very similar sensitivity to the LM139 one [16]. The effect of δV_i is also very similar. Higher δV_i is, lower the sensitivity is. Just as for the LM139, most of the transients have amplitudes near saturation.

4.2.13 Conclusion

All the data available on voltage comparators show that:

- All devices have a high sensitivity to heavy ions. For the most sensitive ones, we can expect several events per year on a geostationary orbit. Protons are not a concern as long as the input differential input voltage is kept larger than 30 mV. For most devices, the SET sensitivity may vary strongly with δV_i : LM119 is more sensitive when δV_i is negative. The 139 types and LM111 are more sensitive when δV_i is small.
- When the comparator output is high the transient is negative going. When the comparator output is low, the transient is positive going. Most of the transients reach the power supply voltage rails. Generally, the transient amplitude is generally smaller when the comparator output is low. The worst-case observed FWHM is 5 μ s.

4.3 Operational Amplifiers

4.3.1 Introduction

The available data on operational amplifiers is listed in Table 2. The effect of a SET in an operational amplifier is an output glitch. A large variety of transient waveforms has been observed (positive-going unipolar, negative-going unipolar, or bipolar, and of short or long duration, etc.). Generally, the worst-case glitch has an amplitude limited by the power supply rail and a duration of tens of microseconds. However, in some devices, OP293, LM6144 extremely long transients were observed.

These SETs may be very difficult to mitigate in an analog chain. Careful analysis of the potentially destructive impact of a SET should be performed. If an amplifier is used to trigger a security signal, voting techniques or filtering should be used.

Table 2: List of available data on operational amplifiers

Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /amplifier unless otherwise specified
LM124	NSC	[26, 12, 23, 8]	LET _{th} <3, $\sigma \sim 3 \times 10^{-3}$ (>500 mV transients)
LT1128	Linear Tec	[27]	LET _{th} <3, $\sigma \sim 4 \times 10^{-3}$ (>500 mV transients)
LMC6484	NSC	[28]	LET _{th} <3, $\sigma \sim 2 \times 10^{-3}$ (>500 mV transients)
LM6144	NSC	[12]	LET _{th} <3, $\sigma \sim 7 \times 10^{-2}$ (>250 mV transients)
OP293	AD	[29]	LET _{th} <10, $\sigma \sim 6 \times 10^{-4}$ (>500 mV transients)
OP27	AD	[10]	LET _{th} <3, $\sigma \sim 1 \times 10^{-3}$ (>250 mV transients)
AD623	AD	[30]	LET _{th} <10, $\sigma \sim 1 \times 10^{-3}$ (>500 mV transients)
LM108	NSC	[20]	LET _{th} <2, $\sigma \sim 3 \times 10^{-3}$ (>100 mV transients)
LM108	Motorola	[24]	LET _{th} <2, $\sigma \sim 1 \times 10^{-2}$ (>200 mV transients)
LM108A	Linear Tec	[31]	LET _{th} <7, $\sigma \sim 6 \times 10^{-4}$
RH108	Linear Tec	[31]	LET _{th} <7, $\sigma \sim 6 \times 10^{-4}$
HS3530	Intersil	[1]	LET _{th} <2, $\sigma \sim 2 \times 10^{-3}$ (>100 mV transients)
LM148	Fairchild	[32]	LET _{th} <3, $\sigma \sim 2 \times 10^{-5}$ (>500 mV transients)
RH1056	Linear Tec	[31]	LET _{th} <2, $\sigma \sim 1 \times 10^{-3}$
OP05	AD	[1]	LET _{th} <3, $\sigma \sim 5 \times 10^{-4}$ (>100 mV transients)
OP07	AD	[33]	LET _{th} <13, $\sigma \sim 2 \times 10^{-4}$ (>1V transients)
OP15	AD	[1]	LET _{th} <3, $\sigma \sim 1 \times 10^{-3}$ (>100 mV transients)
OP42	AD	[20]	LET _{th} <3, $\sigma \sim 2 \times 10^{-3}$ (>200 mV transients)
OP727	AD	[34]	LET _{th} <5, $\sigma \sim 5 \times 10^{-4}$
RH1078		[35]	LET _{th} <2, $\sigma \sim 1 \times 10^{-2}$ (>50 mV transients)
OPA2347	TI	[36]	LET _{th} <5, $\sigma \sim 2 \times 10^{-4}$
AD524	AD	[37]	LET _{th} <11, $\sigma \sim 1 \times 10^{-3}$ (>1V transients)

4.3.2 LM124

Fig 23 shows the LM124 cross-section curve for different bias conditions [26]. We can see that the device sensitivity is similar for all tested conditions. Fig 24 shows the transients amplitude versus width for one of the tested conditions. All test conditions give similar transient waveforms. The largest transients reach the power supply rails. Therefore, for each bias condition, the maximum transient amplitude will change in function of the distance of the nominal output to the supply rail. Figs 25 to 33 show the nine different transient waveforms of the LM124. The largest transients are the class C transients. Their maximum FWHM is of the order of 20 μ s. No proton data is available on this device, but the results of the MPTB analog board experiment show that the LM124 is sensitive to proton induced SETs. Proton induced SETs represent the majority of observed transients in flight [50].

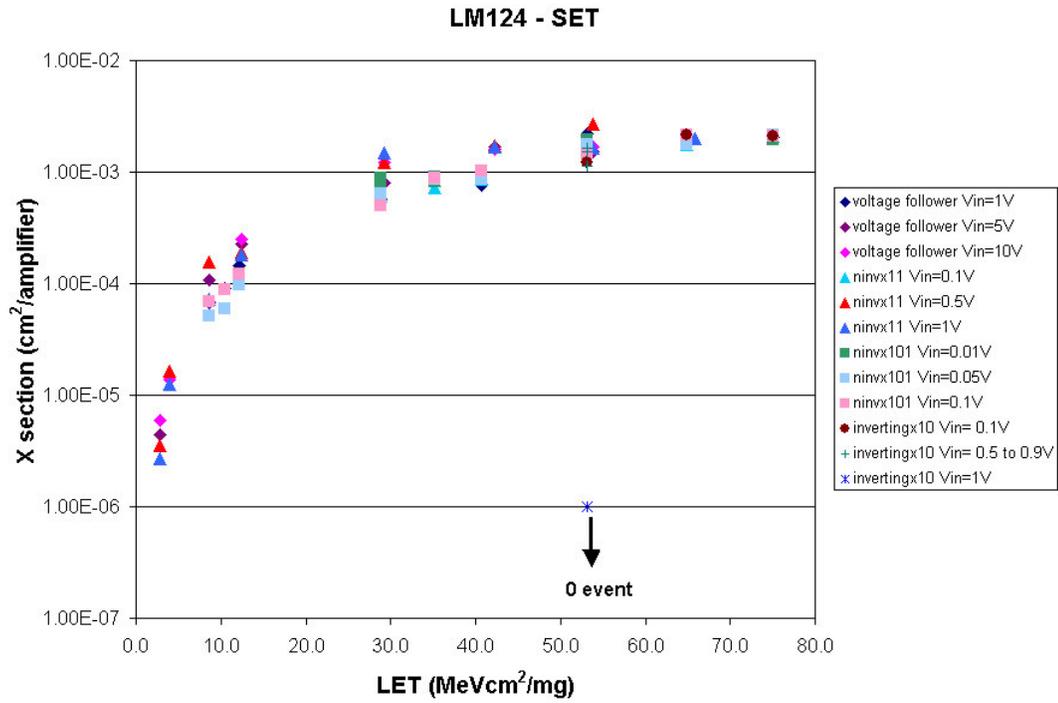


Fig 23: LM124 SET cross-section curves for different bias conditions

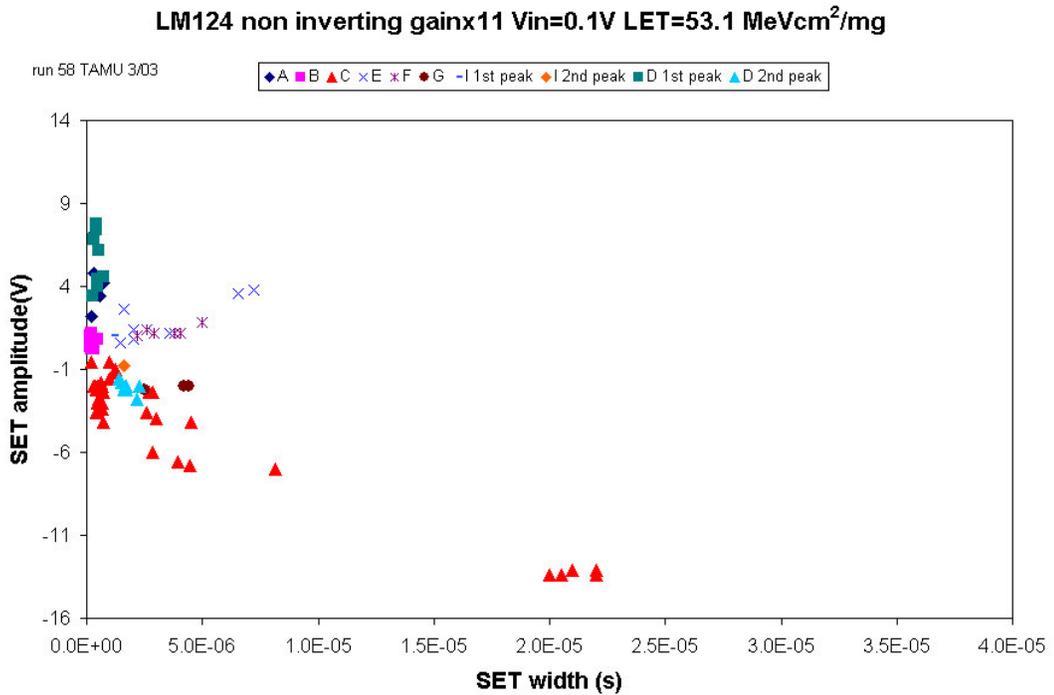


Fig. 24: SET amplitude versus width plot for a non inverting gain x11 application and a 0.1V input voltage

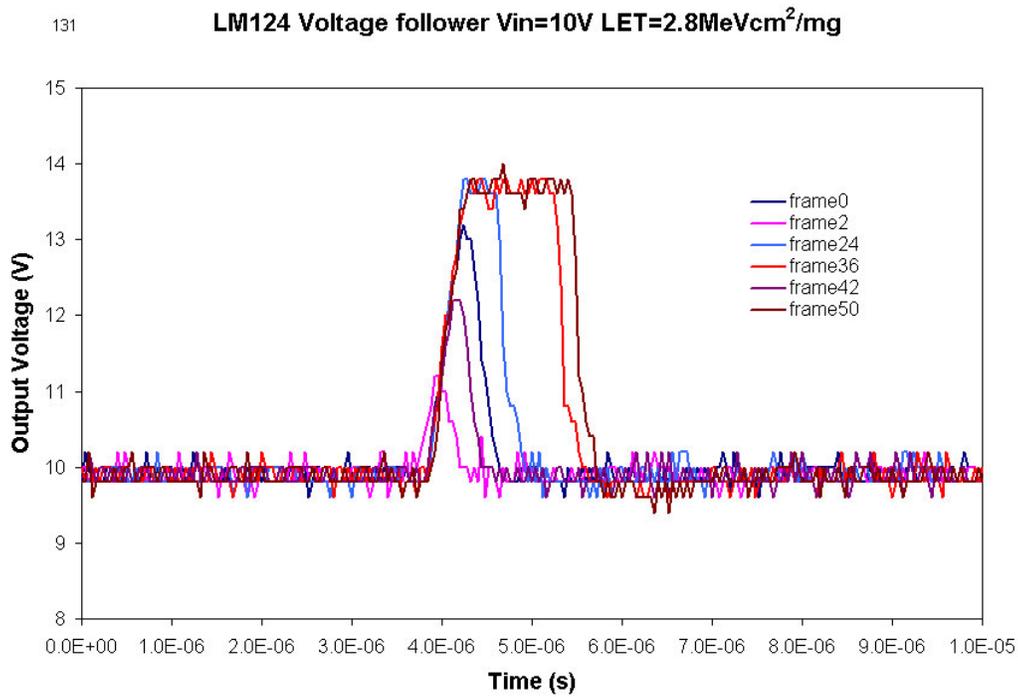


Fig 25: Example of class A transients

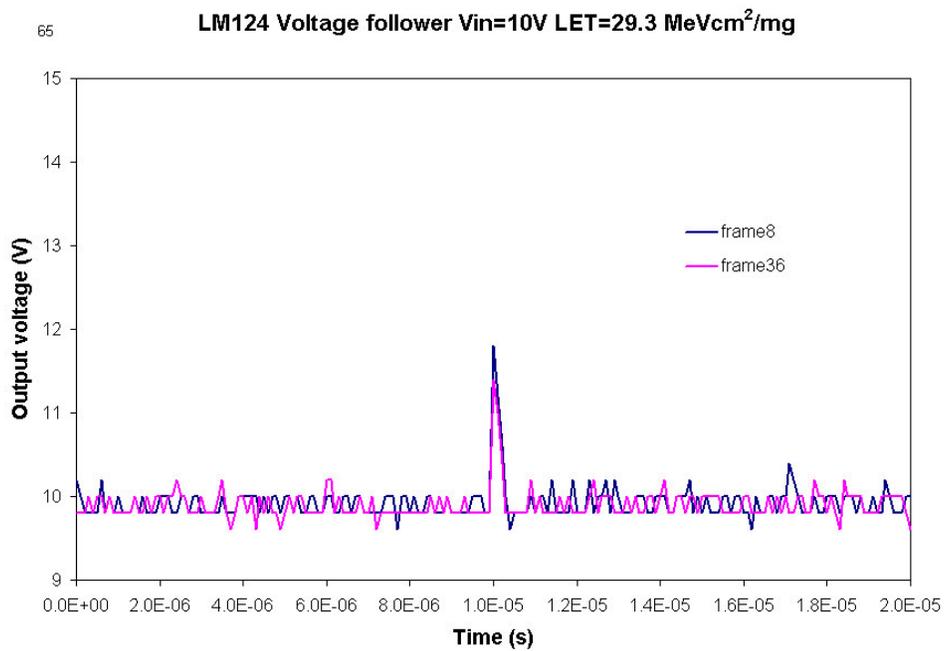


Fig 26: Example of class B transients

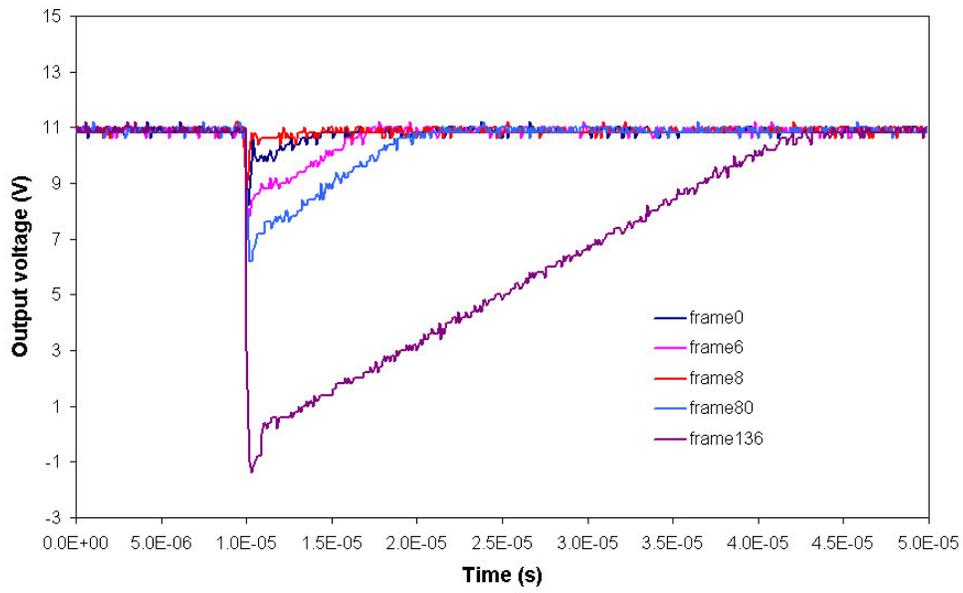


Fig 27: Example of class C transients

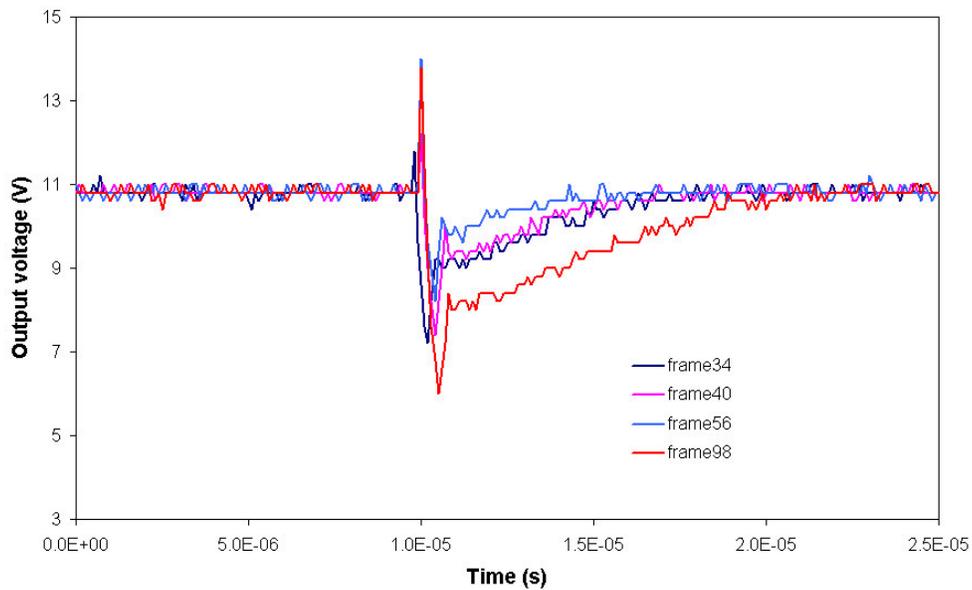


Fig 28: Example of class D transients

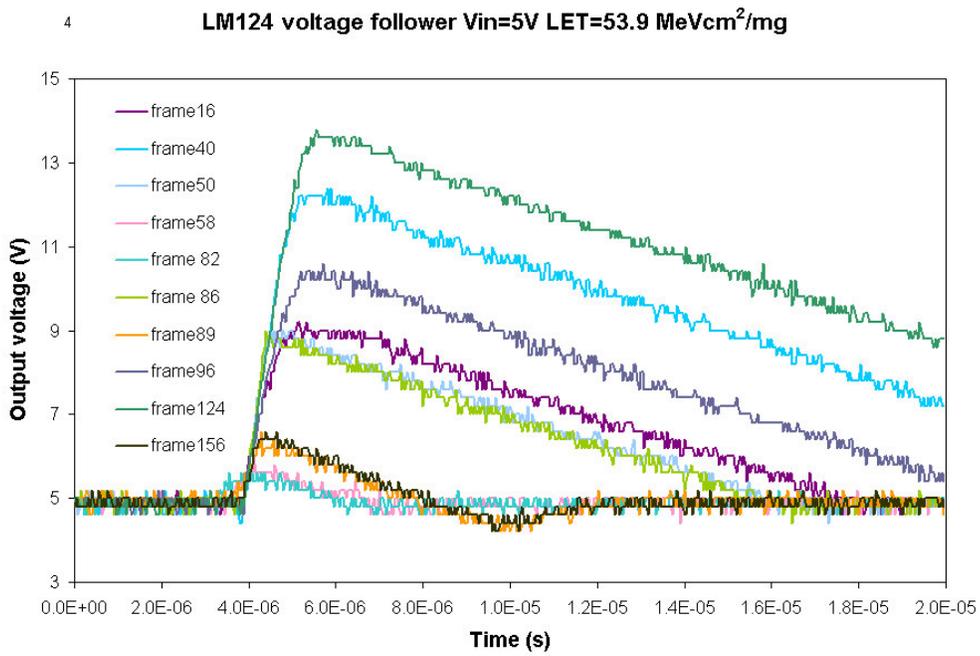


Fig 29: Example of class E transients

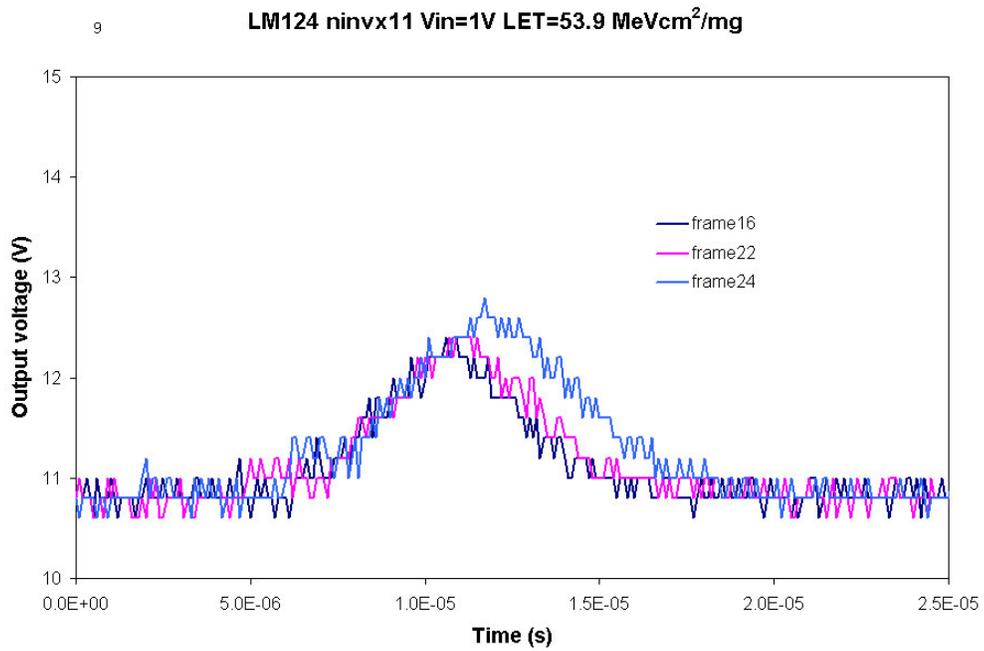


Fig 30: Example of class F transients

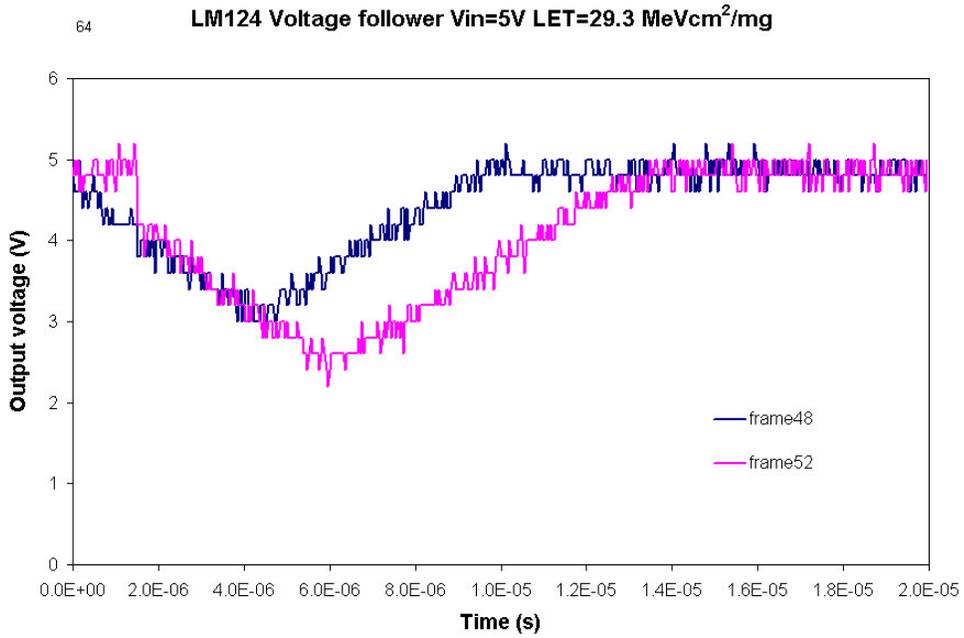


Fig 31: Example of class G transients

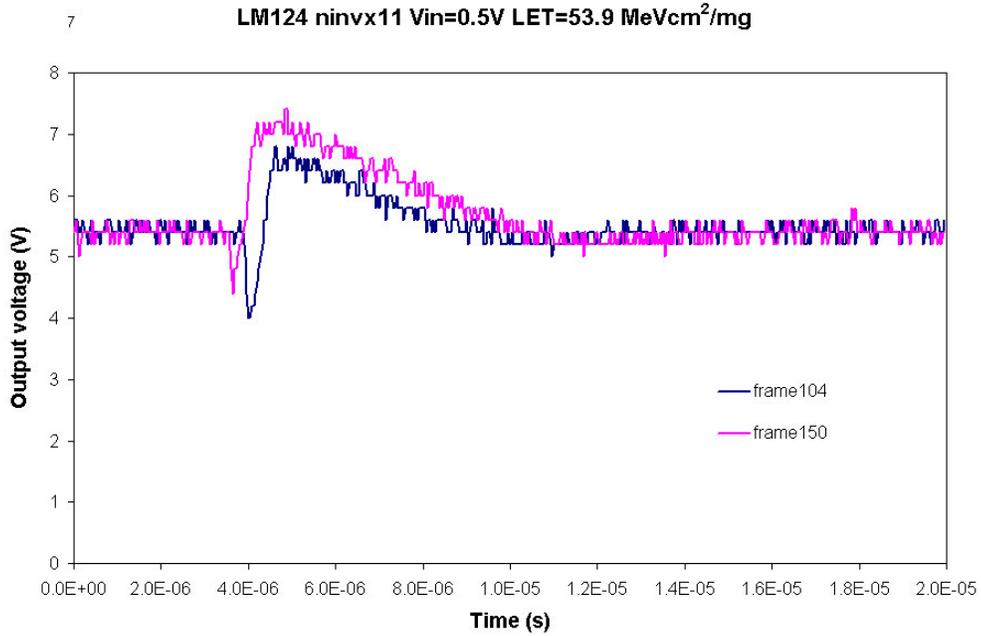


Fig 32: Example of class H transients

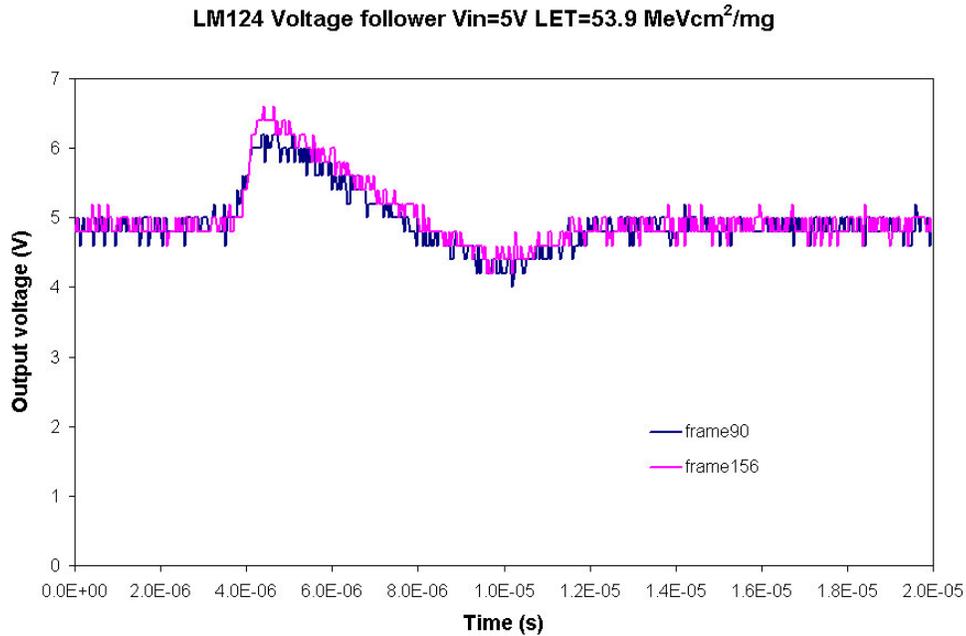


Fig 33: Example of class I transients

4.3.3 LT1128

Fig 34 shows the LT1128 SET cross section curve for different bias conditions [27]. As for the LM124, the device SET sensitivity does not change significantly with the bias conditions. Ten different transient waveforms were identified. Figs 35 to 40 show the 6 most common transient waveforms. Fig 41 and 42 show SET amplitude versus width for the voltage follower and inverting gain applications respectively. We can see in Fig 41 and 42 that the LT1128, contrary to the LM124, shows different responses in the voltage follower and inverting gain applications. For example, class A transients dominate the device's transient response for the voltage follower application, but they are quasi non-existent in the non-inverting gain application. And, class F transients dominate the device's transient response, but do not appear in the voltage follower application. The maximum transient amplitude is about 5V (class E, A, F, C, and B transients) and the maximum FWHM is about 10 μ s. (class D, I, and J).

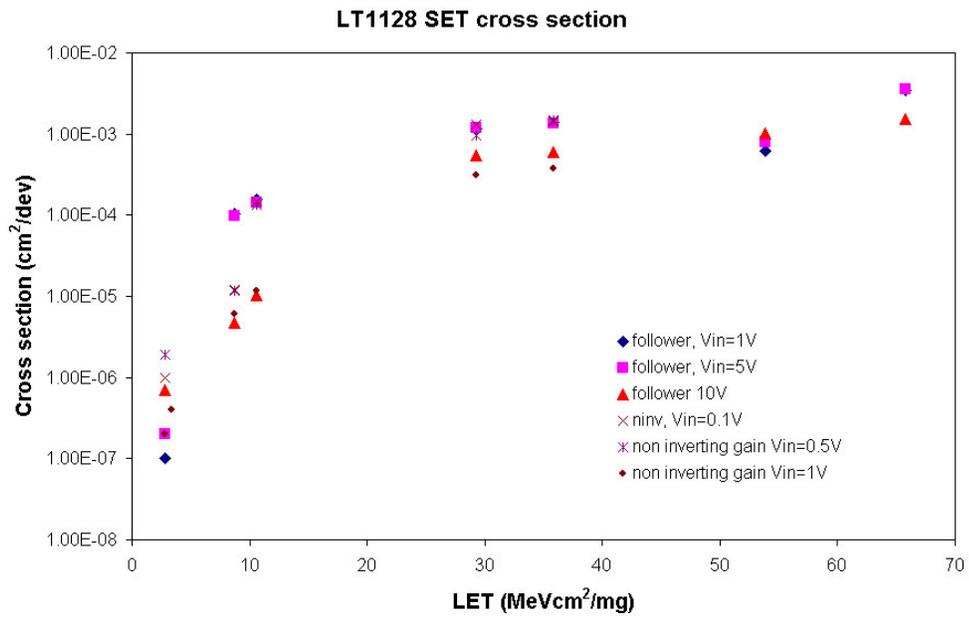


Fig 34: LT1128 SET cross-section curve

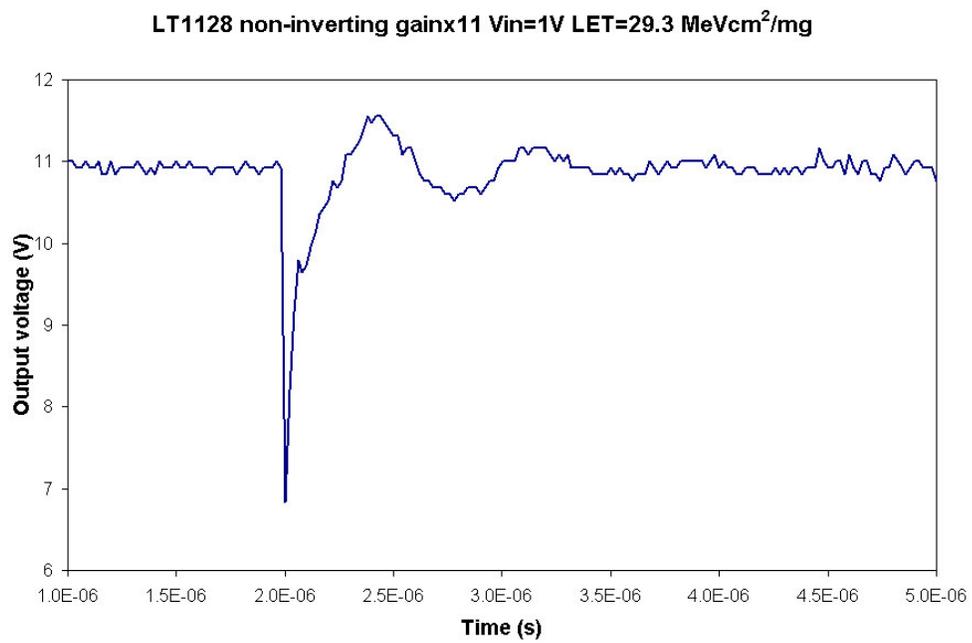


Fig 35: class E transient waveform

LT1128 Voltage follower $V_{in}=1V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

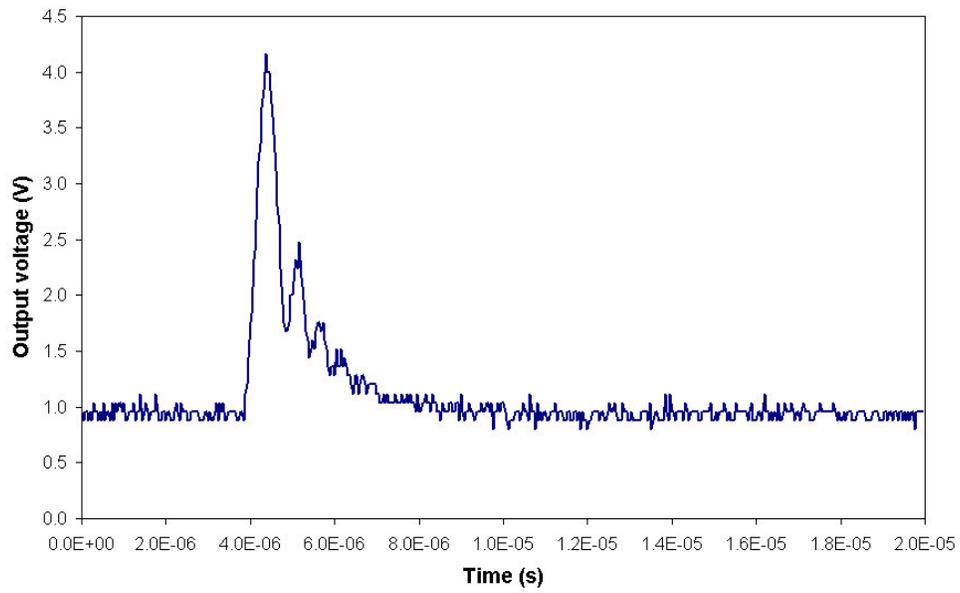


Fig 36: class A transient waveform

LT1128 non inverting gainx11 $V_{in}=0.5V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

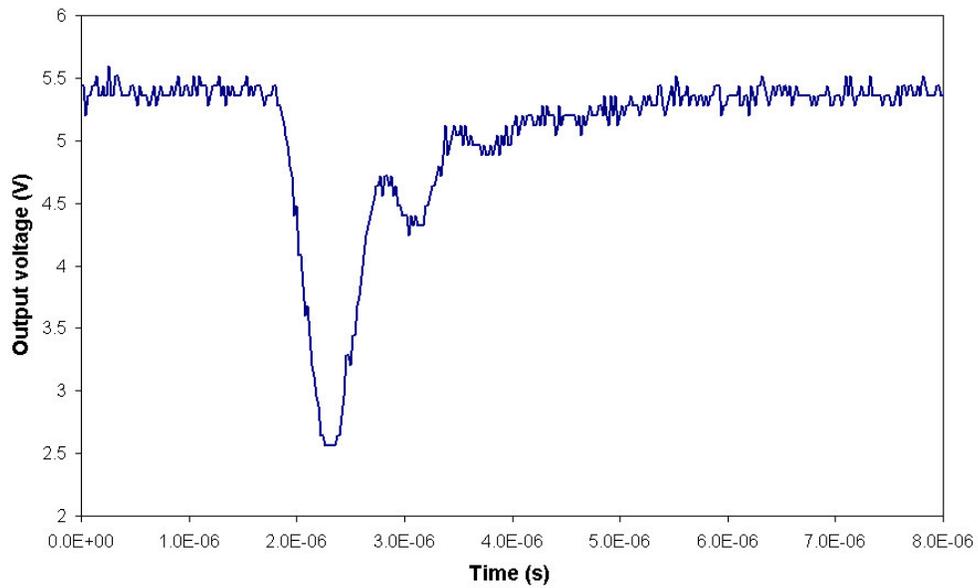


Fig 37: class F transient waveform

LT1128 Voltage follower $V_{in}=1V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

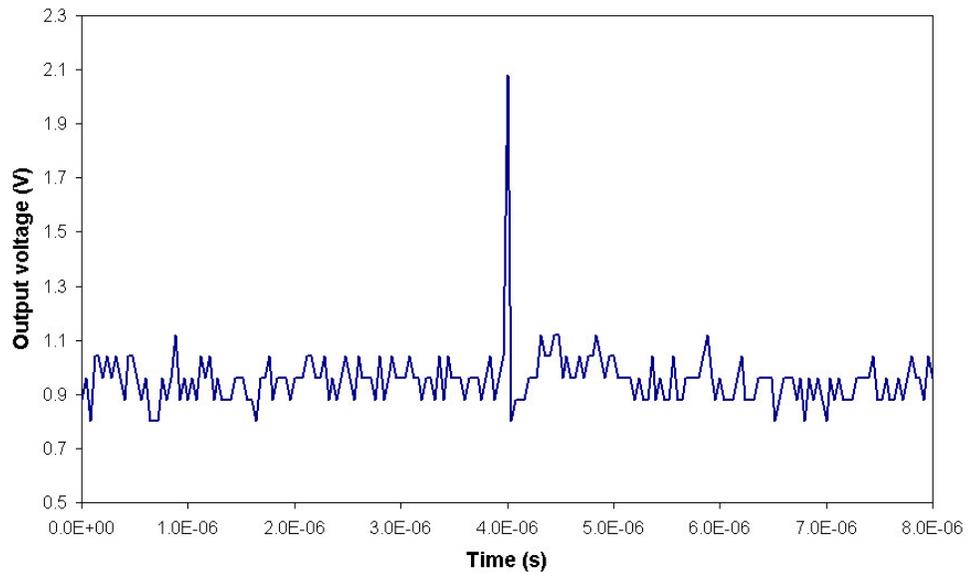


Fig 38: class C transient waveform

LT1128 non inverting gainx11 $V_{in}=0.5V$ $LET=8.7 \text{ MeVcm}^2/\text{mg}$

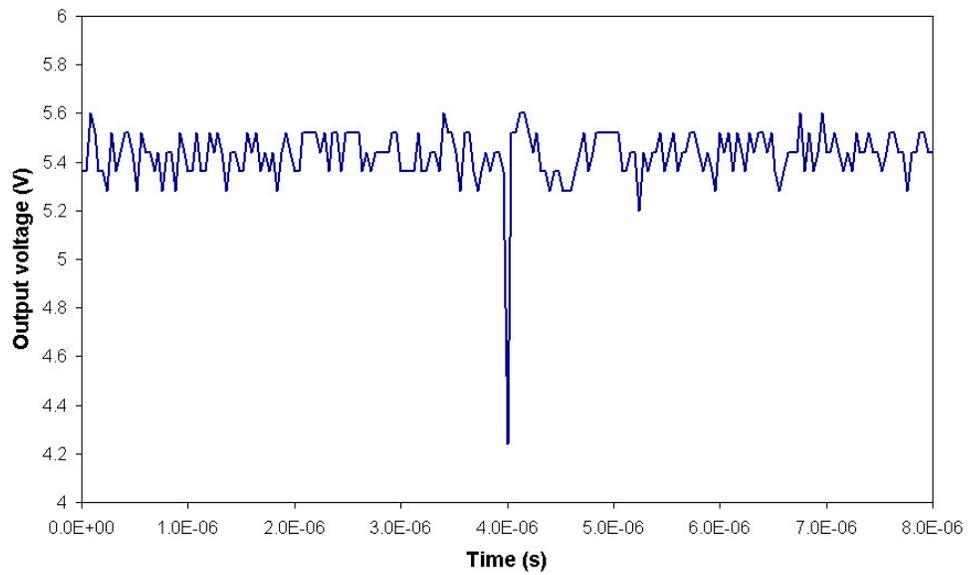


Fig 39: class B transient waveform

LT1128 non inverting gainx11 Vin=0.5V LET=29.3 MeVcm²/mg

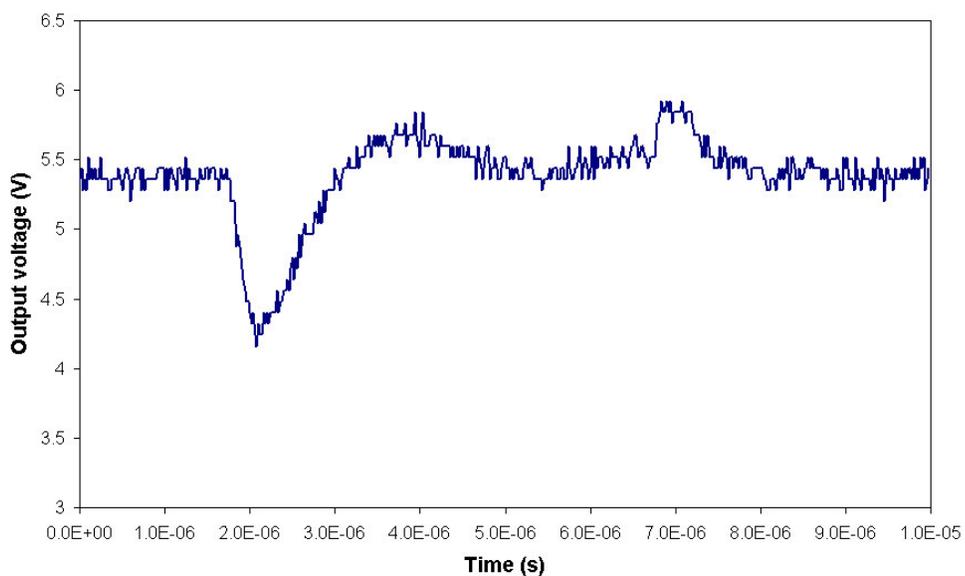


Fig 40: class D transient waveform

LT1128 Voltage follower Vin=5V LET=53.9 MeVcm²/mg

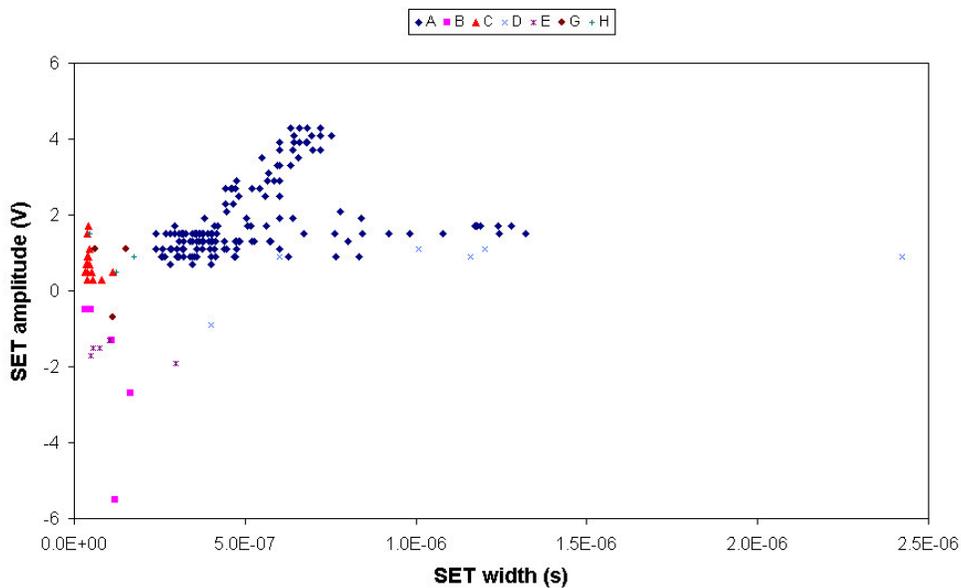


Fig 41: SET amplitude versus width plot for a voltage follower application and a 5V input voltage

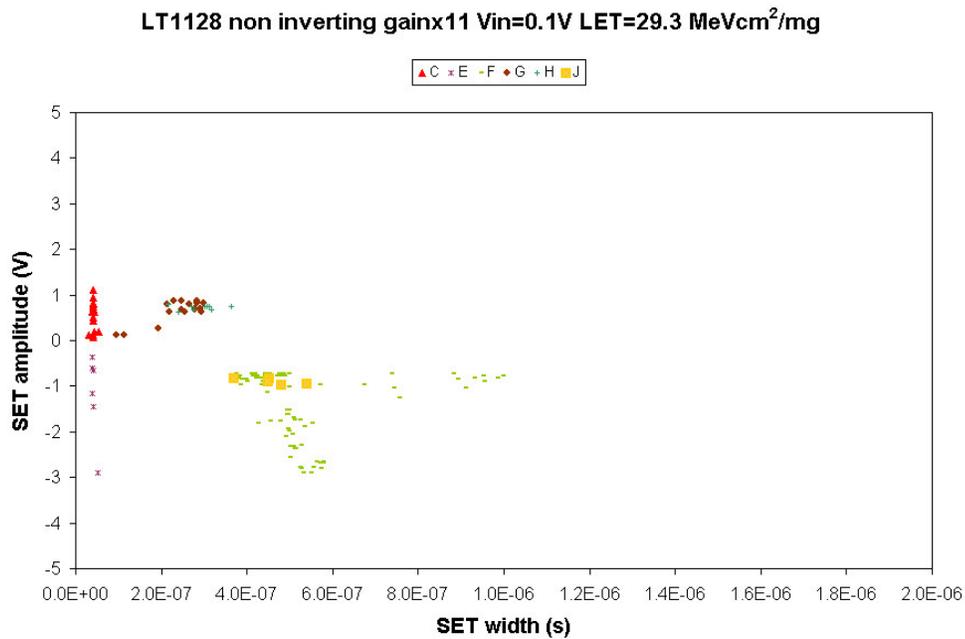


Fig 42: SET amplitude versus width plot for the inverting gain x 11 application and a 0.1V input voltage

4.3.4 LMC6484

LMC6484 is a CMOS operational amplifier that can only be used in an unipolar mode. Fig 43 shows the LMC6484 SET cross-section curve for different bias conditions [28]. Again, the device SET sensitivity does not change significantly with the bias conditions. Five different transient waveforms were identified. Figs 44 to 48 show the transient waveforms. Fig 49 shows the SET amplitude versus width plot for voltage follower application. This plot does not change significantly for the different conditions tested. The largest transients reach the supply voltage rails. The maximum FWMH is about 3.5 μ s (large negative going transients)

LMC6484

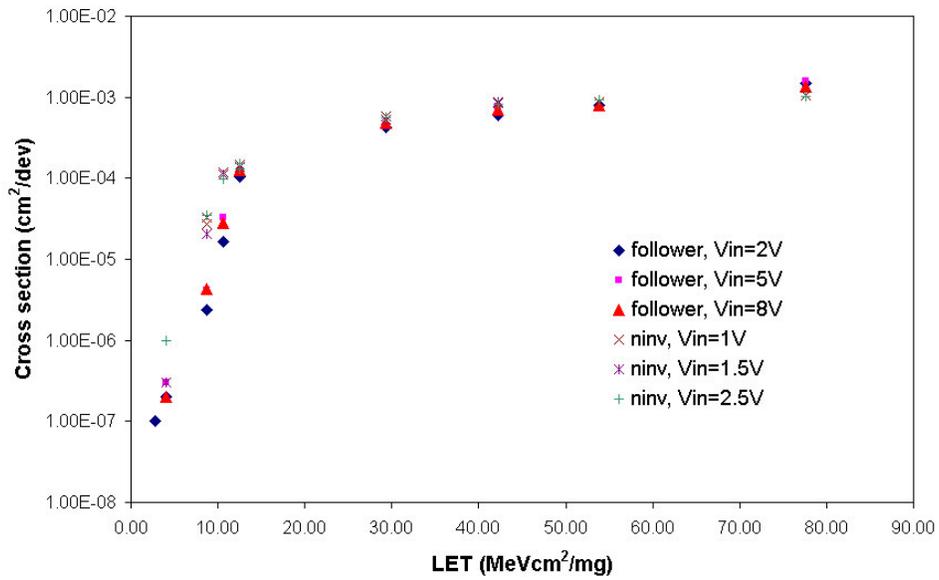


Fig 43: LMC6484 SET cross-section curve

LMC6484 Voltage follower Vin=5V LET=23.9 MeVcm²/mg

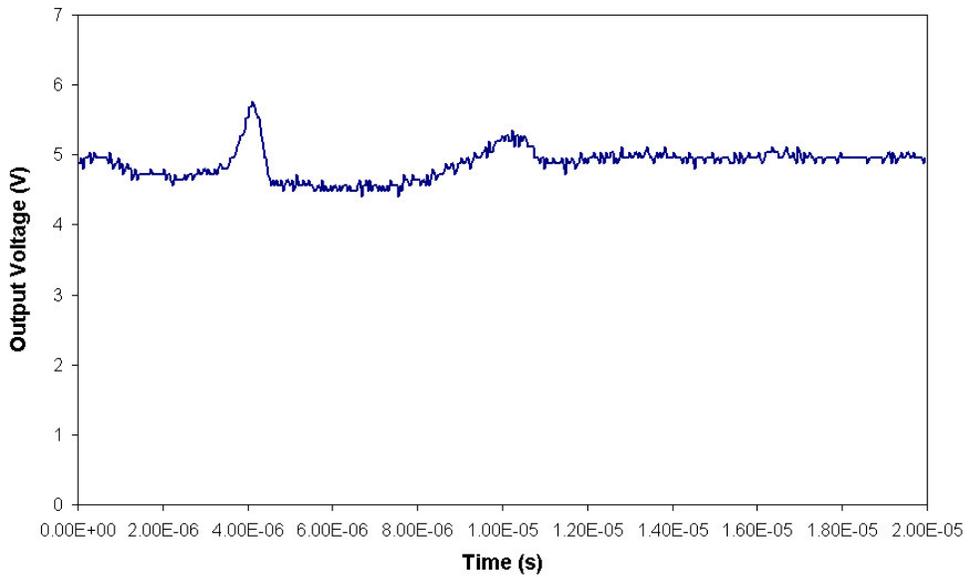


Fig 44: Oscillation waveform

LMC6484 Voltage follower $V_{in}=5V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

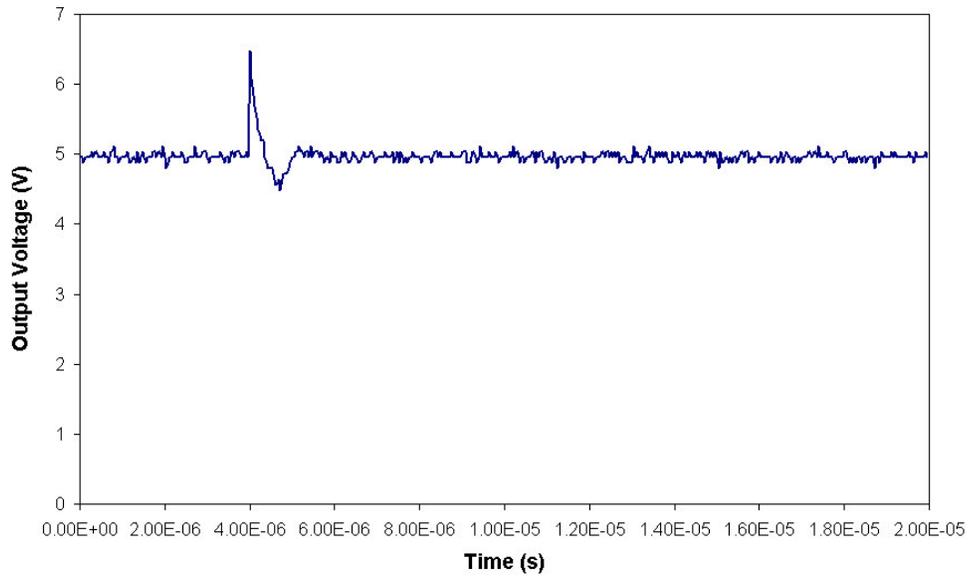


Fig 45: bipolar waveform 1

LMC6484 voltage follower $V_{in}=5V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

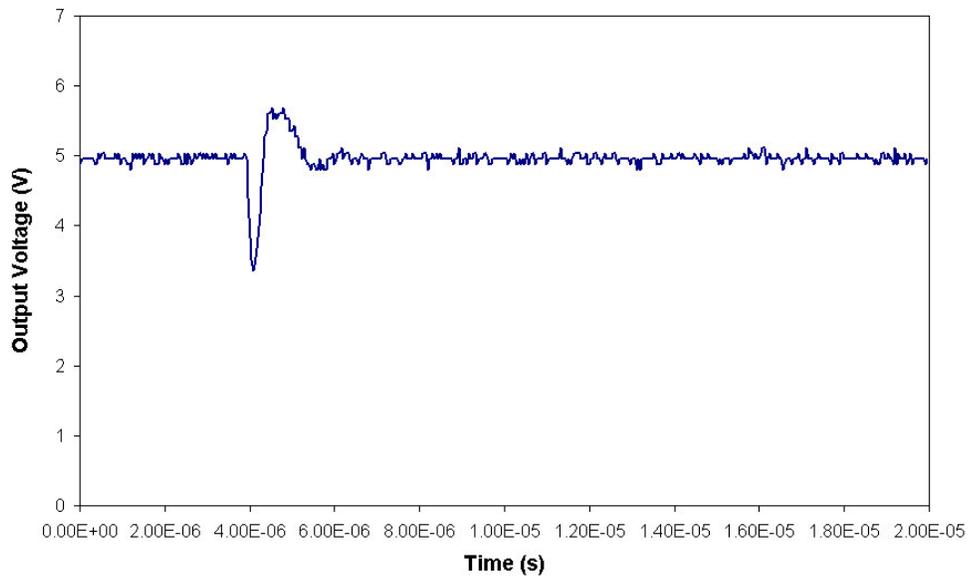


Fig 46: bipolar waveform 2

LMC6484 Voltage follower $V_{in}=5V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

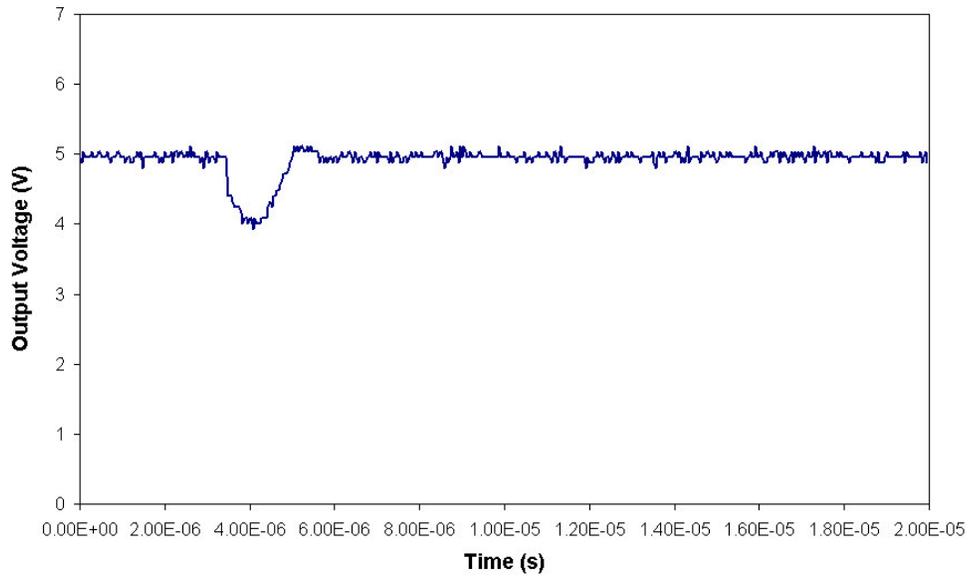


Fig 47: Small amplitude negative going transient

LMC6484 Voltage follower $V_{in}=5V$ $LET=29.3 \text{ MeVcm}^2/\text{mg}$

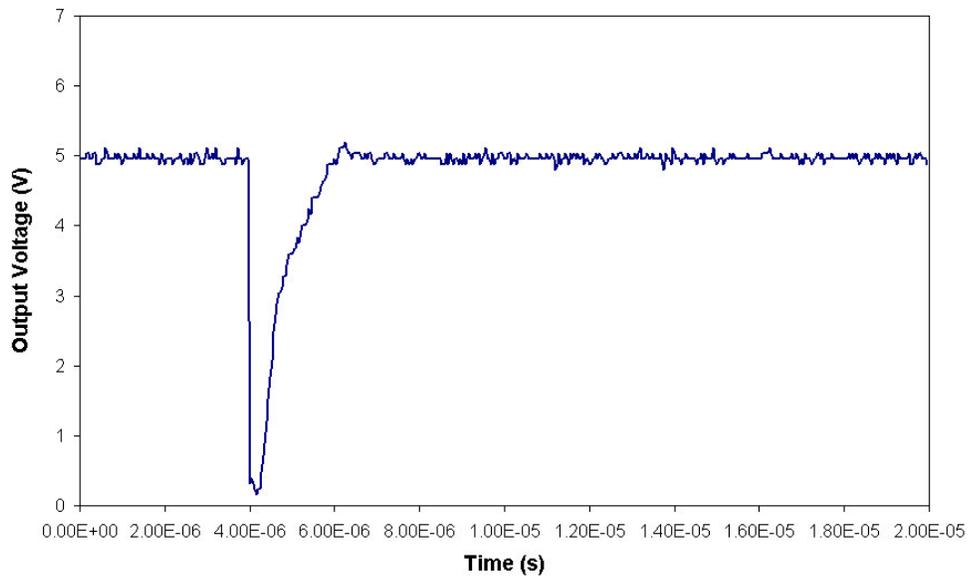


Fig 48: large amplitude negative going transient

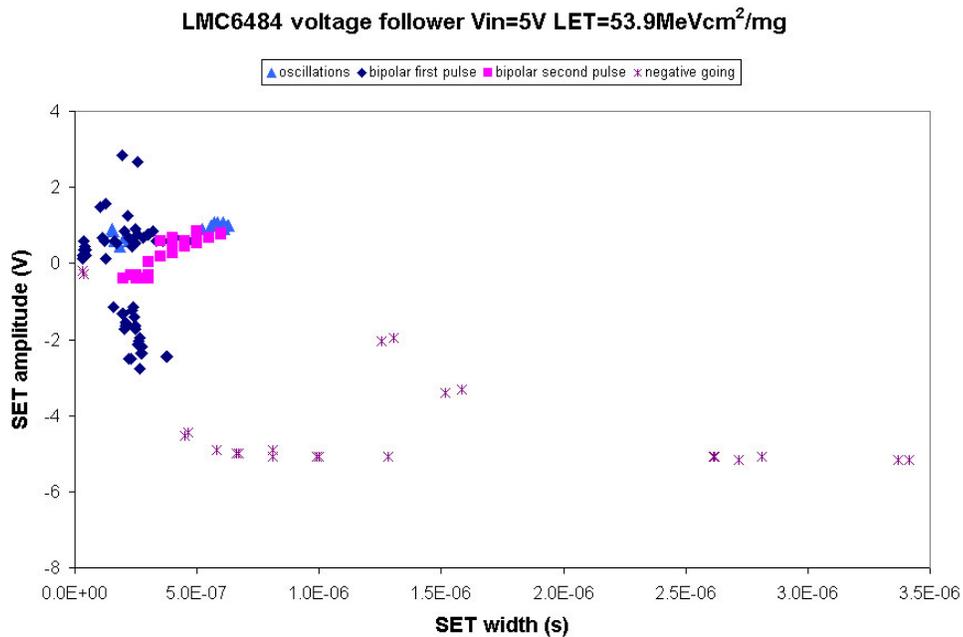


Fig: 49: SET amplitude versus width plot. For the oscillating transients, only the first component is plotted.

4.3.5 LM6144

Figs 50 to 52 show the SET cross-section curves for the inverting gain, non-inverting gain, and voltage follower applications respectively [12]. Figs 53 to 55 show SET amplitude versus width plots for the voltage follower application. We can see that the application does not change significantly the part response. Fig 56 to 59 show the four different classes of transient observed. The amplitude of the class B transients is limited by the supply voltage rails. Most of transient have a FWHM lower than $2 \mu s$ (classes A to C). We can see extremely long transients, with duration up to 1 ms (worst-case measured). These transients represent a small, but not negligible, part of the total device's response.

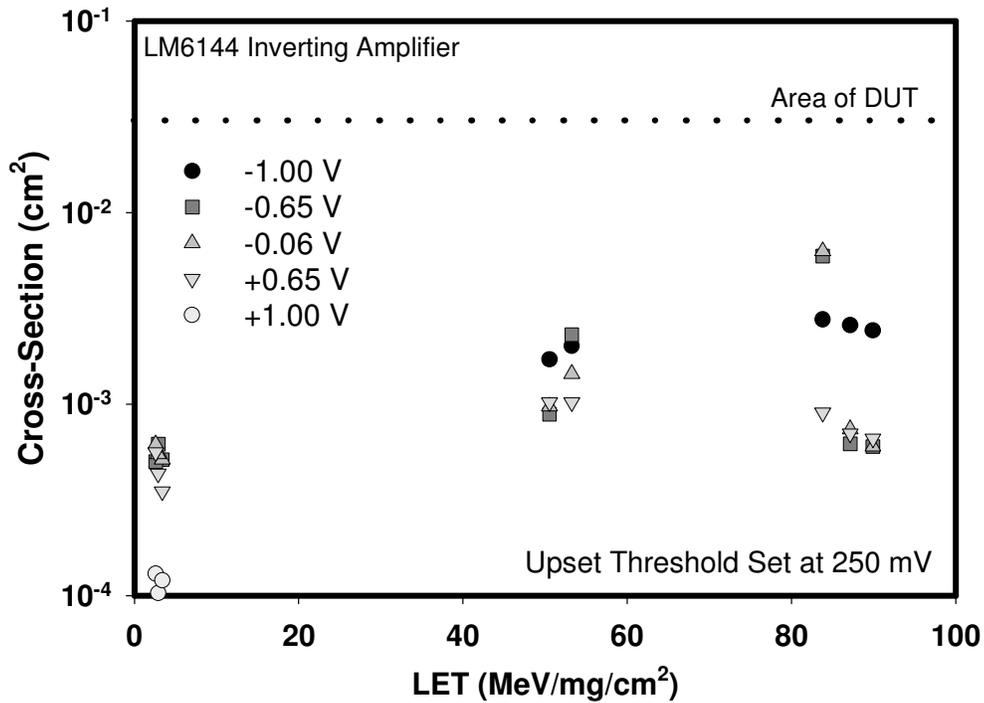


Fig 50: SET cross-section for the inverting amplifier application [12]

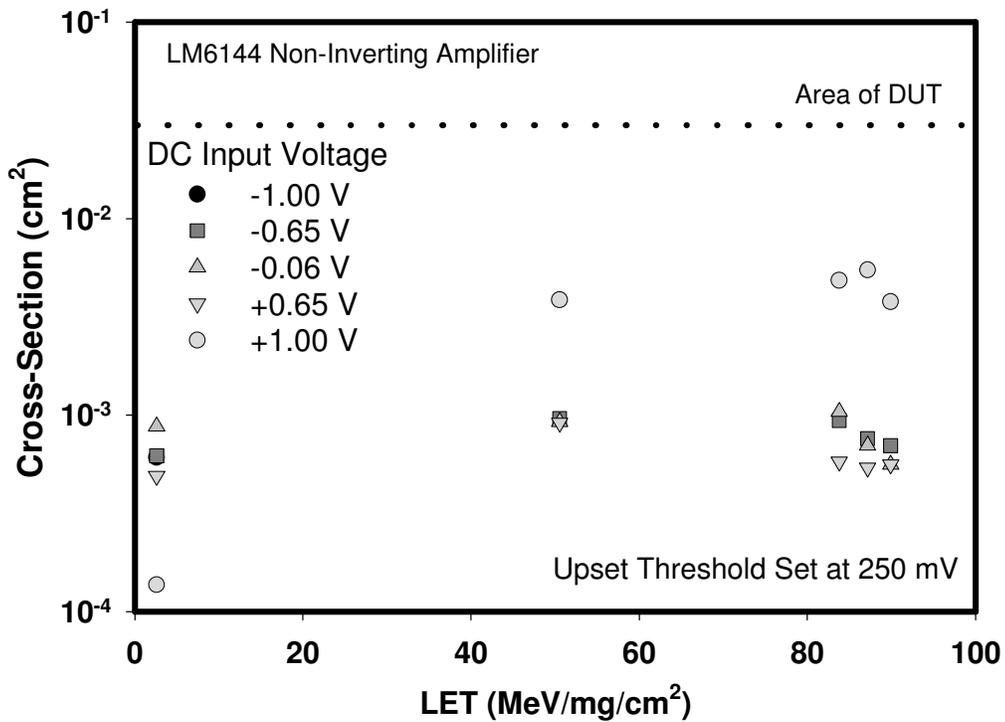


Fig 51: SET cross-section for the non-inverting amplifier application [12]

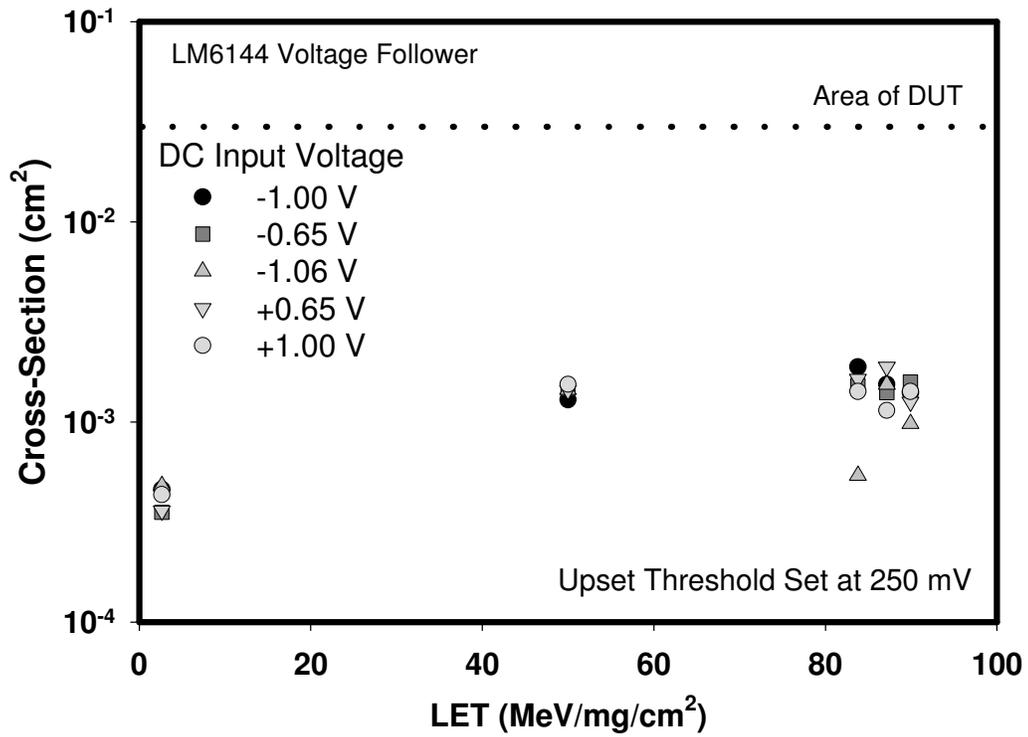


Fig 52: SET cross-section for the voltage follower application [12]

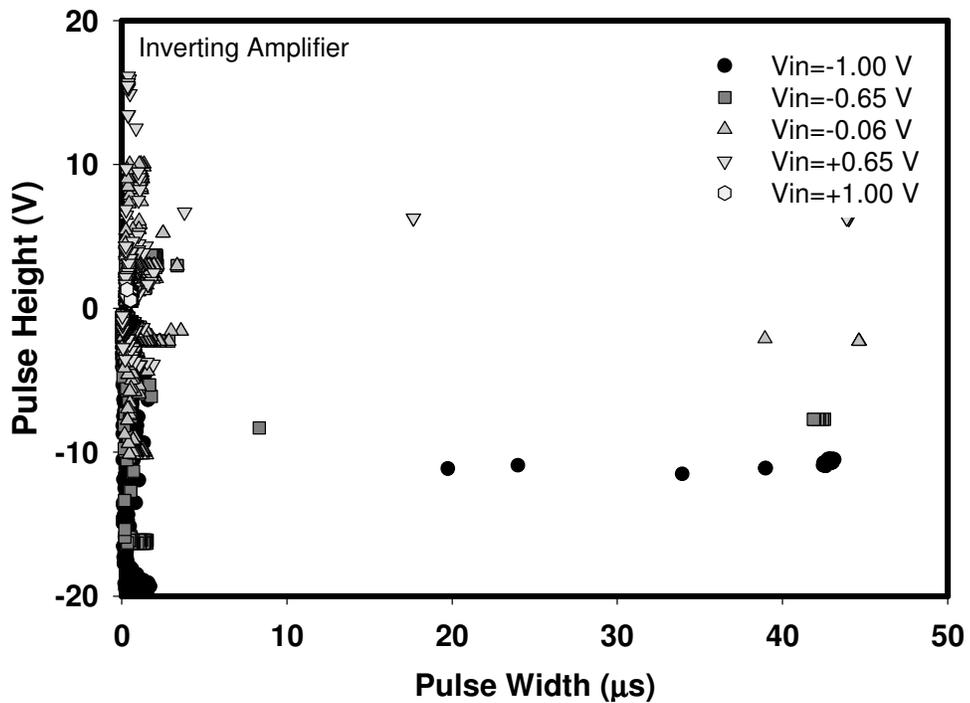


Fig 53: transient amplitude versus width for the inverting gain application [12]

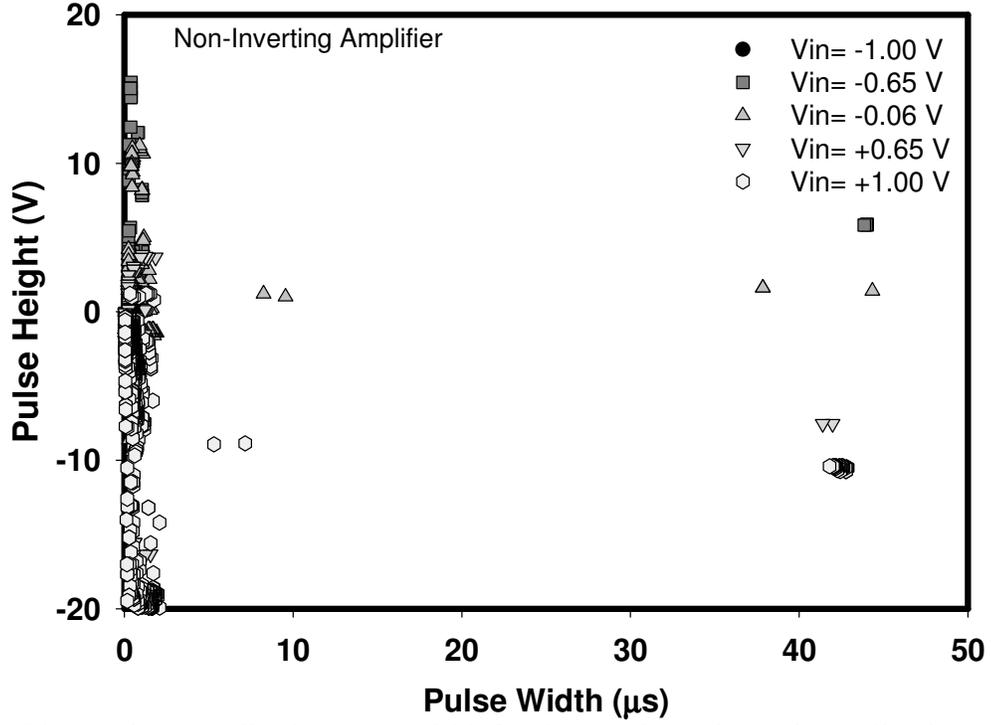


Fig 54: transient amplitude versus width for the non-inverting gain application [12]

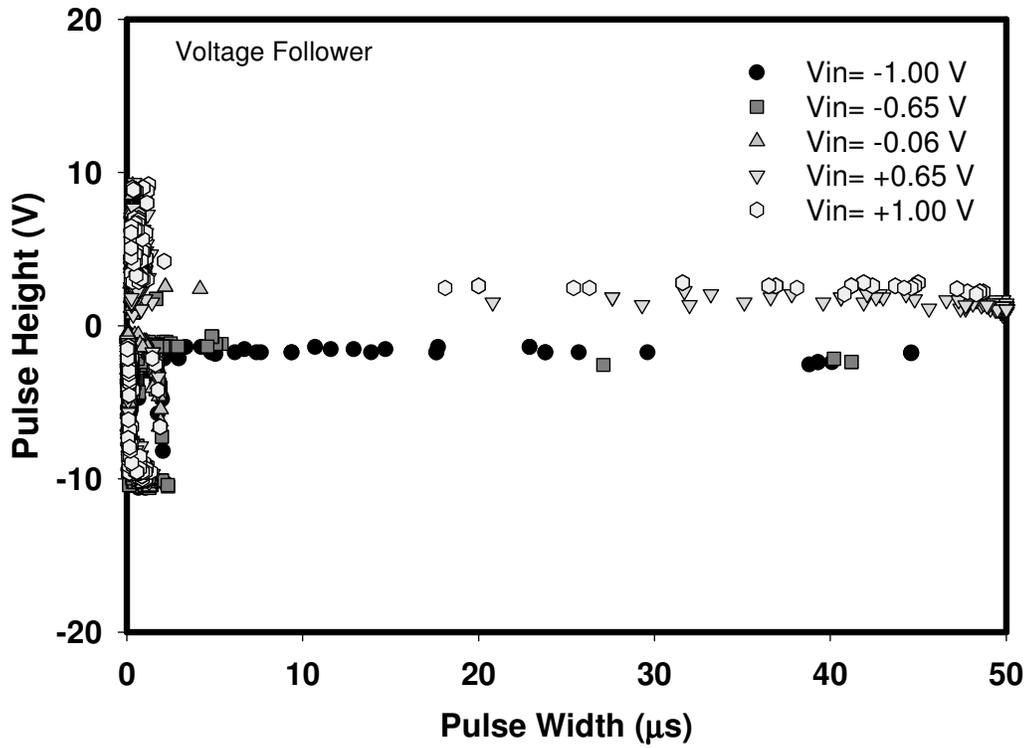


Fig 55: transient amplitude versus width for the voltage follower application [12]

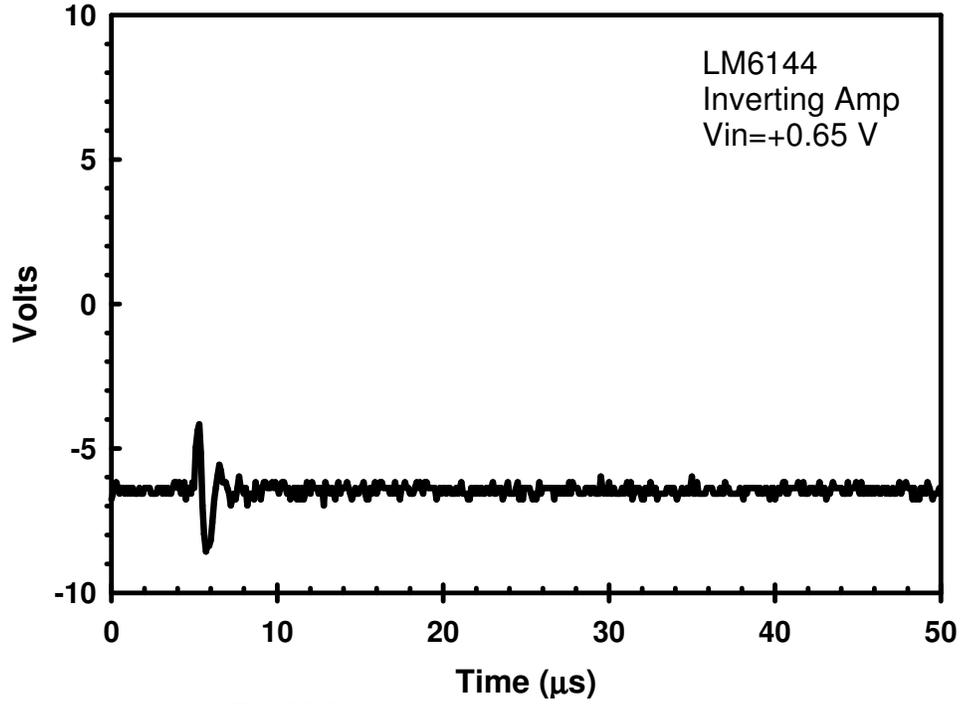


Fig 56: bipolar transient (subset A) [12]

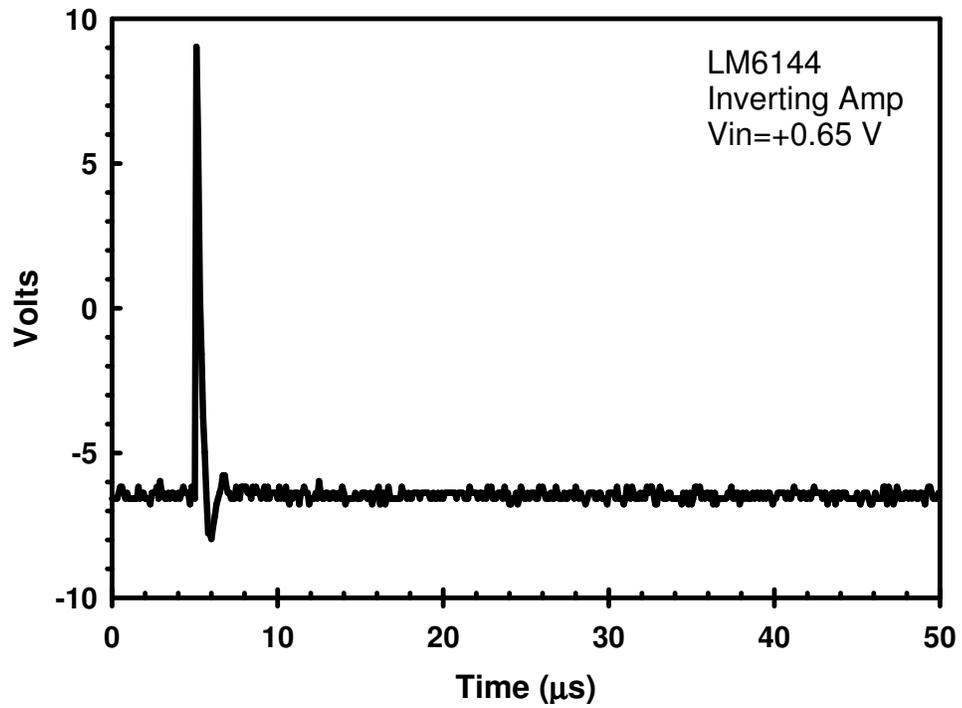


Fig 57: large positive going transient (subset B) [12]

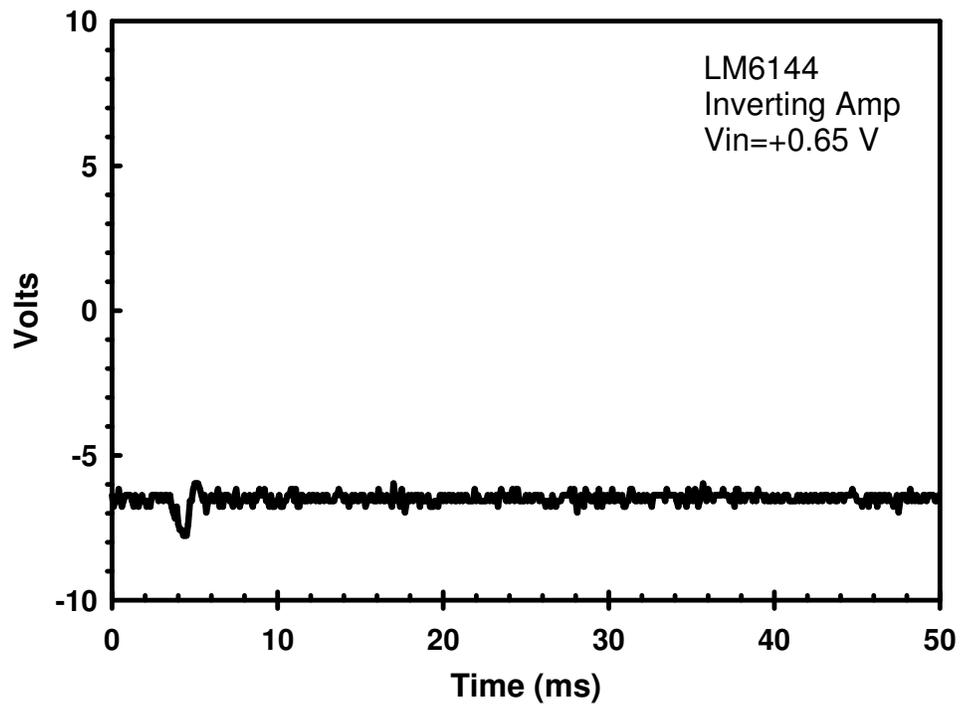


Fig 58: negative sharp going transient (subset C) [12]

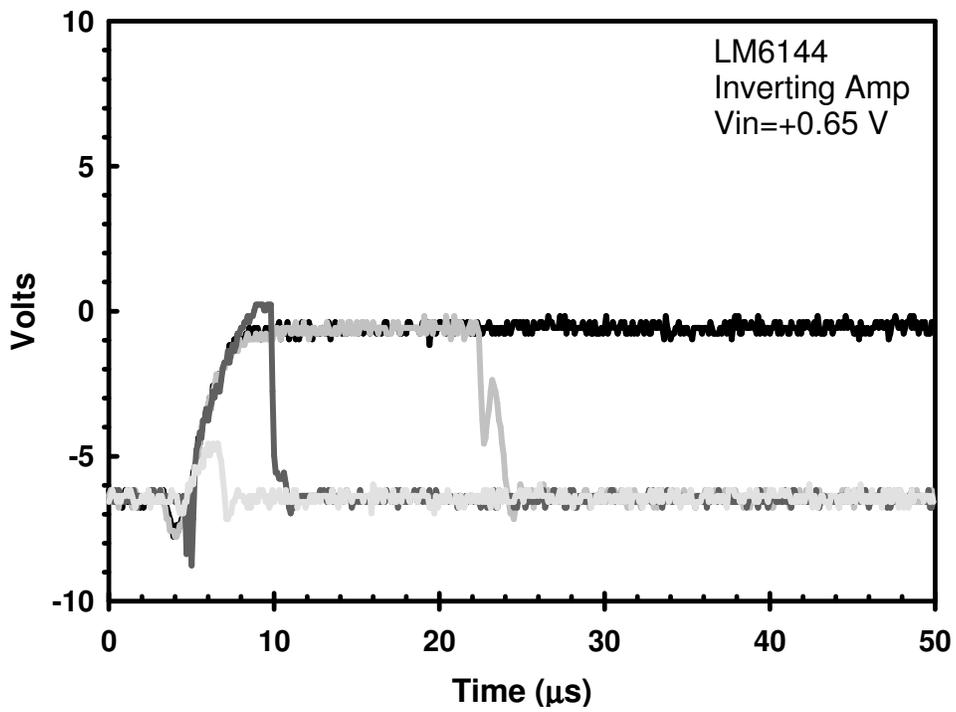


Fig 59: long transients (subset D) [12]

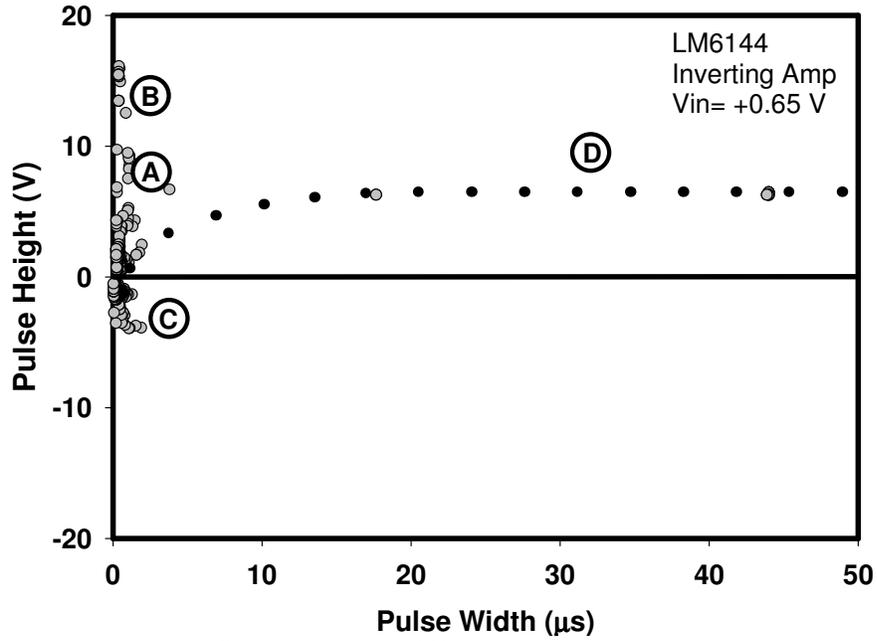


Fig 60: identification of the different transients type in the SET amplitude versus pulse width plot [12]

4.3.6 OP293

Only a partial SET test has been performed on this part, for only one bias condition. The most noticeable result is that extremely long transients were also observed on this device [29]. Fig 61 shows typical waveforms of these long transients. The long transient maximum amplitude is 4V and the maximum FWHM is 200 μ s.

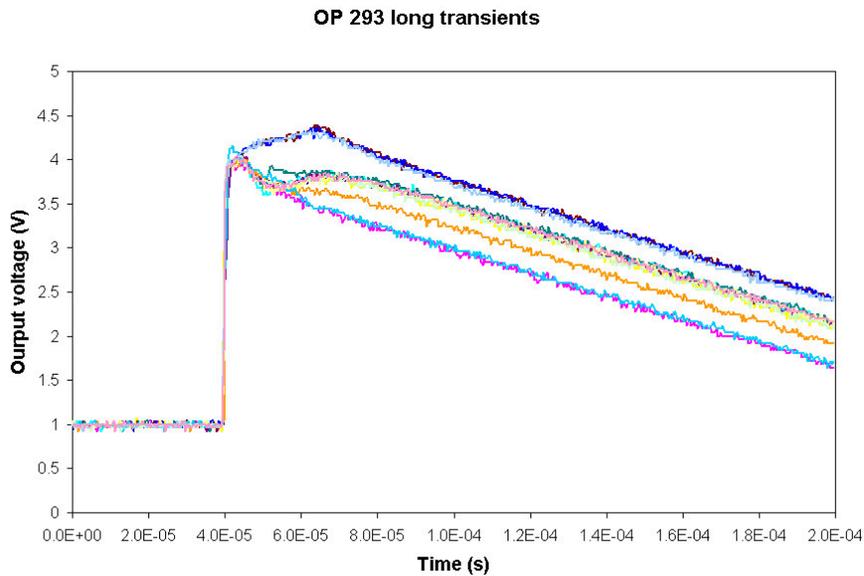


Fig 61: Typical long transient waveforms

4.3.7 OP27

The OP27 cross-section curve is shown in Figure 1. The input bias conditions do not change the device sensitivity. Fig 2 shows the SET amplitude versus FWHM for one of the tested conditions. The largest transients reach the power supply rails and the longest observed transient has a duration of 10 μs [10].

4.3.8 AD623

Only a limited transient testing was performed on this device as well. The SET LET threshold has not been determined. It is expected to be low, around 1 MeVcm^2/mg , based on the cross section curve shape [30]. The largest transients reach the supply voltage rail and their maximum duration is about 20 μs .

4.3.9 LM108

4.3.9.1 LM108 NSC

The input voltages do not change significantly the device's sensitivity [20]. No quantitative information about the transient size is given. The author only reports a large variety of transient heights, from a few mV to larger than 1V.

4.3.9.2 LM108 Motorola

The sensitivity of Motorola LM108 is similar to the one of NSC LM108. Neither the value of the gain nor the input voltage levels influenced the device sensitivity [24].

4.3.9.3 LM108A Linear Technology

The worst-case transient has a 13V amplitude and a 14 μs duration [31].

4.3.9.4 RH108A Linear Technology

The results are very similar to those obtained on the non-hardened device [31].

4.3.10 HS3530 Intersil

A large variety of waveforms, including oscillating ones, has been observed [1]. The largest observed transient has a 4V amplitude and a duration of 3 μs .

4.3.11 LM148 Fairchild

Various pulse height and widths were observed. The transients pulses were generally less than 2 V with the largest pulse heights reaching about 17V. The typical SET duration was about 3 ms with the largest duration around 30 μ s [32].

The device was also tested with 63 MeV protons. With the same detection threshold of 500 mV than the one used for the heavy ions test, no SET was detected to a fluence of $7.4E11$ p/cm².

4.3.12 RH1056 Linear Technologies

The worst-case transient has a 8V amplitude and 15 μ s duration [31].

4.3.13 OP05 Analog Devices

The worst case transient has a 0.8V amplitude and 15 μ s duration [1].

4.3.14 OP15 Analog Devices

The worst case transient has a 1.3V amplitude and 12 μ s duration [1].

4.3.15 OP42 Analog Devices

No effect on the input voltage was observed on the device's sensitivity. The worst case transient has an amplitude larger than 1V [20].

4.3.16 OP727 Analog Devices

The LET threshold is between 3 and 5 MeVcm²/mg and the maximum cross section is about $5E-4$ cm²/device. The largest transients reach the power supply voltage rail and have a duration of about 10 μ s [34].

4.3.17 RH1078 Linear Technology

The largest transients have amplitude of 2 V and duration of about 30 μ s [35]. This device was also tested with protons. The large majority of proton-induced transients are small transients of amplitude between 50 mV and 400 mV. Only 4 transients of amplitude larger than 400 mV were observed with the highest energy and a fluence of $5E10$ p/cm². The maximum measured cross-section with 300 MeV protons is about $2E-8$ cm²/amplifier [6].

4.3.18 OPA2347

This BiCMOs instrumentation amplifier is sensitive to Single Event Latch-up (SEL) for effective LET as low as 11.95 MeVcm²/mg with limiting cross-section of the order of $2E-4$ cm². The SET LET threshold has not been determined, but based on the cross section curve shape, it is expected to be of the order of 1 to 5 MeVcm²/mg. The largest transients reach the power supply voltage rails and have durations of up to 10 μ s [36].

4.4 Voltage References

4.4.1 Introduction

The available data on voltage references is listed in Table 3. The effect of a SET is an output glitch. The best way to mitigate such effects is by the addition of a filter at the device output.

Table 3: List of available data on voltage references

Part Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /device unless otherwise specified
REF-02	AD	[20]	LET _{th} <3, σ ~1x10 ⁻³ (>1V transient)
LT1009	Linear Tech	[38]	LET _{th} <3, σ ~2x10 ⁻³ (>200 mV transient)
RH1009	Linear Tech	[38]	LET _{th} <3, σ ~2x10 ⁻³ (>200 mV transient)
IS1009	Intersil	[38]	LET _{th} <3, σ ~2x10 ⁻³ (>200 mV transient)
REF-043	AD	[38]	LET _{th} <3, σ ~2x10 ⁻³ (>200 mV transient)
AD584	AD	[39]	LET _{th} <2, σ ~1x10 ⁻² (>30 mV transient)

4.4.2 REF-02

A wide range of pulse heights was observed both positive and negative going from the nominal quiescent 5V output. However, there were substantially more transients with small amplitude than those with larger amplitude [20].

4.4.3 2.5V precision voltage reference type 1009

4.4.3.1 Introduction

The four device types have a similar SET sensitivity. The majority of SET are of small amplitude. The dominating transients are negative going pulses. Positive going SET are less frequent and of much lower amplitude. The maximum amplitude of positive going transients is 0.5V.

4.4.3.2 LT1009 from Linear Technology

The largest transient is going down to the ground level, and has 3 μs duration. The device has also been tested with different capacitive loads. With a 10 nF load, the LET threshold increases to 10 MeVcm^2/mg , but the maximum cross-section does not change [38].

4.4.3.3 RH1009 from Linear Technology

The RH1009 is TID radiation hard version of LT1009 from Linear Technology. The cross section is similar to the one of LT1009. However the transient characteristics and their evolution with the load are different [38]:

- Without load, the number of transients of amplitude larger than 1V is smaller.
- For the highest capacitance load of 100 nF, the total cross-section of SET of amplitude greater than 200 mV is reduced by a factor 30.
- Small amplitude transients have a longer duration especially for higher capacitance loads. Their maximum duration is 8 μs without load and 17 μs for the highest load.

4.4.3.4 IS 1009 from Intersil

The radiation hard voltage reference from Intersil shows the same SET sensitivity than the LT1009. However, the transient characteristics are different: The largest transients that reach the ground rail are the ones with the longest duration. Their maximum duration is about 5 μs [38].

4.4.3.5 REF43 from Analog Devices

The LET threshold of this device is higher than the one of the other 1009 type devices. Without load, there are only a few transients of amplitude larger than 1V. With load there is no transients larger than 0.5V and the transient duration is shorter. The duration of small amplitude transients is longer than the one observed on the other devices. The maximum duration observed is 10 μs [38].

4.4.4 AD584 Analog Devices [39 ESA/HIREX report]

Most of the transients have small amplitude. The LET threshold for SET of amplitude larger than 300 mV is about 12 MeVcm^2/mg , and the maximum cross section is about $1\text{E-}3 \text{ cm}^2$.

Both positive going and negative going transients were observed. The maximum amplitude of positive going transients is 500mV, and the maximum amplitude of the negative going transients is about 2V. The maximum transient duration is 10 μs .

4.5 Voltage Regulators

Table 4 shows the only data available on voltage regulators. The device tested was not sensitive up to a LET of 75 MeVcm²/mg. We expect the same behavior on most voltage regulators. The eventual SETs are generally filtered by the large capacitors used at the devices' output in typical applications. Therefore, no specific action is typically necessary for such devices.

Table 4: Available data on voltage regulators

Part Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /device unless otherwise specified
LTC1149	LTC	[40]	LET _{th} >75 (typical application bias, 200 μ F output capacitor)

4.6 MOSFET Drivers

4.6.1 introduction

Little data is available on these devices. The available data is listed in Table 5. The sensitivity varies from type to type. Generally, the result of SET is a glitch at the device's outputs. For devices implementing a shutdown function, a SET in this function may cause the device to shutdown, and device reset or power cycle may be necessary to recover functionality.

Table 5: available data on MOSFET drivers

Part Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /device unless otherwise specified
TSC4429	Teledyne	[41]	LET _{th} >120
UC1707	Unitrode	[42]	Shutdown latch validated: LET _{th} ~3, σ ~1x10 ⁻³ cm ² /output (transient) LET _{th} ~3, σ ~7x10 ⁻⁴ cm ² /device (shutdown) Shutdown latch not validated: LET _{th} ~10, σ ~4x10 ⁻⁴ cm ² /output (transient)

4.6.2 UC1707 from Unitrode/TI [42]

In addition to the driver circuitry, this device has an analog shutdown function with an optional latch. Therefore, in addition to the transients that can happen at the device output due to SETs in the driver circuitry, transients can happen at the device output due to transients in the analog shutdown voltage comparator circuitry when the latch is disabled. When the latch is enabled, SEUs in the latch that may be induced by transient in the shutdown function voltage comparator, shutdown the device outputs. A reset of the latch or a device power cycle is necessary to recover device functionality.

When the latch is validated, the driver output transient LET threshold is about 3 MeVcm²/mg and the maximum cross section is about 1E-3cm² per device output. And, the worst-case

shutdown LET threshold is about 3 MeVcm²/mg and the maximum cross-section is about 7E-4 cm²/device. The sensitivity to shutdown varies with the voltage comparator input differential voltage. This shows that the voltage comparator transients contribute significantly to the number of latch upsets. Proton testing was also performed in this condition, results that the shutdown event sensitivity depends on the shutdown function input bias conditions. For large δV_i , the device is not sensitive. For small δV_i , proton induced 4 driver output events and 4 shutdown events were observed with 300 MeV protons over a fluence of 2E11 p/cm².

When the latch is not validated, the driver output transients LETthreshold is about 10 MeVcm²/mg and the maximum cross-section is about 4E-4 cm²/output. The contribution of the voltage comparator transient to the total number of transients at the device output is very small.

The driver output transients are all negative transients that reach the ground rail. Their maximum duration is about 8 μ s.

4.6.3 Conclusion

Generally, the short output perturbations should not be critical for most applications. On the contrary, for devices implementing shutdown functions, the shutdown events may be critical. It is recommended to use designs with automatic restart to mitigate these events.

4.7 Analog switch

Table 6 the only available data on analog switches. The result of a SET will be an output perturbation because the switch goes on for a short period of time when it is off and vice versa.

Table 6: available data on analog switches

Part Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /device unless otherwise specified
ADG452	Analog Devices	[43]	$\sigma \sim 1 \times 10^{-5}$ cm ² /switch at LET=59.3

4.7.1 ADG452 Analog Devices

Only a limited test at high LET, greater than 59.3 MeVcm²/mg, was performed [43]. The sensitivity is small. When the switch is on, the SET have small amplitude of about 0.5V maximum and a duration of about 300 μ s. When the switch is off, the SET have large amplitude. The largest transients can reach the supply voltage rails. The largest measured transient duration is about 500 μ s.

4.8 Analog MUX

Table 7 shows the data available on analog MUX. The device tested was not sensitive to SET. The expected effect of a SET in an analog multiplexor is a temporary perturbation of the device output.

Table 6: available data on analog MUX

Part Type	Manufacturer	Data Reference	Summary of Results LET in MeVcm ² /mg σ in cm ² /device unless otherwise specified
338RP/MAX338	Maxwell	[44]	LET _{th} > 79

4.9 Pulse Width Modulators (PWM)

Three different types of SET have been identified:

- (1) **Shutdown events:** Both outputs return to a low output state for a period of time correlated with the soft start feature or the shutdown feature of the device. The time it takes the duty cycle to increase from 0% to D_{cmax} after the onset of the upset is equal to the time it takes to discharge and recharge the soft start capacitor.
- (2) **Short output perturbations:** The second type of SEU has a disturbance of much shorter duration. These short disturbances come in two forms. In the first form, the complementary outputs both return to the low reference. This event lasts for less than one clock period after which they would return to normal output amplitude and frequency. The second form of upset manifests as a toggling of the outputs not related to the clock. The correct function is restored after one or two clock cycles.
- (3) **Clock event:** The third type of SEU is a phase shift of the clock circuit. The outputs follow the change in the clock phase. This event also affects the device frequency output. Therefore, depending on how the device is used in a circuit, this sort of upset can affect more than one function of the device.

Generally, the two last types of SET do not affect the operations of the applications where PWM are used (mainly DC/DC converters). This is due to the short duration of the event. On the contrary, the first type of SET could have an impact on the application depending on the soft start circuitry. The longer the duration of the soft start, the higher the impact on the application. It could be very critical on application where no auto restart circuitry is implemented. After shutdown, the device never starts again. The PWMs that do not implement the soft/start and/or shutdown functions are not sensitive to this type of events.

The list of available data on PWM is presented in Table 7

Table 7: list of available data on PWM

Part Type	Manufacturer	Data Reference	Summary of Data LET in MeVcm ² /mg σ in cm ² /device unless otherwise specified
SG1525	Linfinity	[45]	Type 2 only: LET _{th} ~5, σ ~1x10 ⁻⁴
UC1802	Unitrode / TI	[46]	Type 1: LET _{th} ~3, σ ~2x10 ⁻⁵ Type 2: LET _{th} ~3, σ ~6x10 ⁻⁴
UC1806	Unitrode / TI	[47]	Type 1: LET _{th} ~5, σ ~1x10 ⁻⁵ Type 2: LET _{th} ~5, σ ~1x10 ⁻³
UC1825A	Unitrode / TI	[46]	Type 1: LET _{th} <3, σ ~1x10 ⁻³ Type 2: LET _{th} <3, σ ~1x10 ⁻² Type 3: LET _{th} ~5, σ ~2x10 ⁻⁴
UC1845	Unitrode / TI	[46]	Type 2 only: LET _{th} ~3, σ ~2x10 ⁻⁴
UC1825	Unitrode / TI	[48]	Type 1: LET _{th} <60, σ ~6x10 ⁻⁶ Type 2: LET _{th} <3, σ ~2x10 ⁻³
UC1823	Unitrode / TI	[48]	Type 1: LET _{th} <60, σ ~1x10 ⁻⁶ Type 2: LET _{th} <3, σ ~2x10 ⁻³
UC1856	Unitrode / TI	[48]	Type 1: LET _{th} <5, σ ~1x10 ⁻⁴ Type 2: LET _{th} <3, σ ~1x10 ⁻²

4.9.1 SG1525 Linfinity [45]

Only transients of type 2 were observed. Some of them affect 2 clock cycles.

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