HEAVY ION AND PROTON INDUCED SINGLE EVENT TRANSIENTS IN LINEAR DEVICES

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Abstract

This paper presents a display of heav - ion- and proton-induced single event transients for selected linear devices. The transient vital signs are scrims: low 1,1 ET threshold, high voltage amplitude and extended pulse duration (microsecs.)

1. *Introduction*

investigations of heavy ion induced single event transients (S1 ET) in linear IC's have been pursued for several years (1 ,2), but their impact on spare and satellite systems and a convenient way for describing and handling them is still open to d i scussion.

Our approach is to photograph transients for a selection of devices for a set of key parameters, such as ion 1,1 ET and input polarity. If each photograph contains several snapshots of a series of transients generated under a fixed identical condition, then the photo displays individual device variability such as might arise from ion impacts at different random locations on the chip. By taking the same set of photos for several different heavy ions anti 1 .ETs, one can observe how the transients change with 1,1 ET and also determine the device 1.1 ET threshold.

in this paper, we have applied th is approach to three (li fferent op amps and three different comparators. 1n addition, a sufficient number of data points were taken to develop a heavy ion cross section (for all observed transients exceeding a specified 2V output scope trigger voltage) and a 1 .ET threshold for several device types.

A separate section reports the first proton-induced transients in a linear device-- proof of a well-preclicled result (Ref. 2). Included are details of the transient response of the NSC LM 139 comparator ' to protons of various energies, Ep ≤200 MeV.

11.7710 *Experiment*

A. Devices-- The test devices are described in Table 1. M ore det ai 1s are given in the. individual discussions of device radiation response.

'1'able 1. Test Devices

i .TN 1<111056	op amp-rad bald
LTN LM 108A	op amp
LTN RH 108A	op amp-rad hard
NSC LM139	comparator
NSC LM111	comparator
PMI LM139	comparator

* Note: LTN=Linear Technology, NSC=National Semiconductor, PM I=Precision Monolithics

B. Test Facilities- Heavy ion tests were conducted at the Brookhaven National Laboratory (BNL) Van de Graaff and the Texas A&M (TAM) K500 cyclotron at College Station. The latter has a significantly higher range of energies than BNL, but a lower set of] .ET's (See Table 2.) Two device types, the LTN RH 1056 and NSC LM1 39, were tested at both heavy ion facilities with only a mod est diffe rence in response at equivalent LET.

One device, the NSC 1.M139 comparator, was also tested with protons of energies up to 200 MeV at the. Indiana University Cyclotron Facility (IUCF).

c. Test Setup- The comparators and op amps were set up as shown in Figures 1 & 2, respectively. Note that on the output of both device types there is a divide-by-two circuit and op amp to decouple the outputs from the tester and allow the output to exceed the rails. Note also that there is an input voltage divider for the comparators, but not the op amps. Some noise. problems were encountered at the TAM medium energy heavy ion cyclotron with the op amp test dc.vices, which were mitigated by placing a 1 nanoF capacitor on the feedback. This was a stop-gap measure that affected the shape of SETs somewhat, according to a later comparison using a strobe light. Finally, note the 1μF capacitors on the comparator inputs. Later test data Were obtained without these capacitors, and no significant difference in transient response was noted. A best (standard) test setup has not yet been chosen; in some cases, it may be one that can be easily related to the user's system.

Table 2. Test ions at BNL & TAM

1011.4 Energy	LET*	Range(μ)
TAM		
1961 MeV Xe	44	148
600 MeV Ar	7.3	227
BNL		
286 MeV 1	60	28
276 MeV Br	40	36
280 MeV Ni	26	44
150 MeV Cl	13	42
90 MeV F	4.4	64
98 MeV C [-t angles]	1.45	98

* $MeV/(mg/cm^2)$

III. Heavy Ion Experimental Results

A. General Remarks

Heavy ion data were taken at both BNL and TAM accelerator facilities. The BNL, data were superseded by the TAM data except for threshold determinations at BNL with 98 MeV C, using many incident beam angles. Hence higher LET data is limited to that from the TAM test. Photos were taken for most data runs, using 600 MeV Ar (LET=7.3 $MeV/mg/cm^2$) and 1961 MeV Xe (LET = 44 $MeV/(mg/cm^2)$. Observations were made of LET threshold, device cross section, transient amplitudes, duration and polarity.

Significant heavy ion transients were seen with all six device types. The cross section for each device type is tabulated in Table 3, for the two LETs of TAM ions. in general, the comparators showed a larger amplitude but shorter duration of transients than the op amps. However, the amplitudes are significant in both functional types (ranging from several volts to rail-to-rail) and so is the time. duration (1 to 20 microseconds.) The transit.l]t polarity depends on input polarity in all cases-- a fact that depends on the inherent clamping of the alternate transient polarity.

Table 3. TAM--Transient Heavy Ion Device Cross Sections* (cm^2) for a "Standard" Input**

	LET = 44***	LET= 7.3***
Comparators [25 mV device input gap]		
NSC LM139	5.9 ± 0.5 E-4	1.5E-4
NSC LM111	2.8 ± 0.3 E-4	8.5 E-5
PMI LM139	7 ± 1 E-4	3 E-4
Op Amps [0.5V device input		
LTN RH1056	1.4 E-3	4 E-5
LTN LM108A	6 E-4	picture (rely
LTN RH108A	5E-4	2 E-4

* The cross section is the number of transient events exceeding 2V, divided by the projected beam fluence ($ions/cm^2$).
** There is no difference in cross section with input polarity -- for these high LET's only.
*** $MeV/(mg/cm^2)$

The transient heavy ion LET threshold of most devices were found, using BNL's 98 MeV C as shown in Table 3a. It should be pointed out that the low (0.2V) trigger used for some devices does not permit an exact comparison with the more meaningful 2V trigger which must necessarily have an equal or higher threshold. Only the latter output transients are capable of tripping CMOS circuits. It is also noteworthy that the cosine law for beam angle dependence applied well for these transient threshold determinations.

The transient photos showed a variation in response for each device type, obtained from repeat runs for the same conditions, but this variation is fairly well contained about a characteristic result. This means that one can count the transients without constantly including a rider to specify an amplitude discrimination level. That is, even though one selects a low trigger voltage for defining and counting a transient (2V in this set of data), the large majority of events exceed the trigger level [even near threshold]. This lack of lower-amplitude transients in "a gray zone of uncertain system impact" implies that one can provide a tractable description of the heavy-ion-induced transients. With such information, it is easier to predict error rates in nearby circuitry for a specified radiation environment.

Table 3a. BNL--Transient Threshold LET for "Standard" Inputs & 2V Output Trigger Voltage

Comparators	LET(th)-- MeV/(mg/cm^2) [25mV device input]
NSC LM139	2
NSC LM111	No data
PMI LM139	<<1.45 [10mV input ; high out]
" "	<1.45 [10mV input ; low out]
Op Amps	[0.5V device input]
LTN RH1056	1.7
LTN LM108A	<1.45 [used 0.2V trigger volt]
LTN RH108A	<1.45 [used 0.2V trigger volt]

B. Comparators

Three different bipolar comparators (See Table 1) were tested at room temperature for several different input voltage pairs. [Example: a positive applied input of +25 mV= POS 5.00V/2 and NEG 4.95V/2; a negative applied input of -25 mV=POS 4.95V/2 and NEG 5.00V/2.] The combined comparator data for the two accelerator tests show that the transients of the two manufacturer versions of the LM139 devices retain their large amplitudes and time durations as the beam moved to successively lower LET ions, until we come quite close to threshold. The rail-to-rail comparator outputs (LTN & PMI LM139 only) remained unaffected, but their duration diminishes as we come down in beam LET

It is no coincidence that the variability in comparator output for a fixed set of conditions likewise holds to a steady rail-to rail amplitude with varying pulse widths. We can postulate that variability in response was due to variability in collected charge as a result of the strike location on the chip. The less effective strikes would be expected to behave very much like the lower LET ion hits.

In searching for threshold with various angles of 98 MeV C, it was found that the cosine law behavior held true. This result suggests that a wafer-shaped sensitive volume controls transient generation as it does with SEU's in many IC's.

Photos of Comparator Response

1) NSC LM139-- Photos of Runs 2 and 5 show the response to 1961 MeV Xe [LET = 44 MeV/(mg/cm^2)], with 4.95/5.00V input and its reversal. Many transients are 2.5 µs long, but a few are shorter. Rail-to-rail amplitudes are always the same for each of the sample's three parts. A lower-LET run with 600 MeV Ar (LET=7.3), per photo 34, showed the same rail-to-rail response but

a shorter duration of 1.3 μs. RN], data showed a LET threshold of 2 . 0 MeV/(mg/cm^2).

The cross section [See Table 3] of 5.9 ± 0.s x 10^{-4} cm^2 for LET=44 MeV/(mg/cm^2) is for one of the. four comparators comprising the quad. This result can be compared with unt abul ated BNI , data of 3.4 ±] x 10^{-4}cm^2 for 1.1 ET=40 MeV/(mg/cm^2). The number Of data points is limited in both cases, but the difference exceeds confidence limits. One explanation: the ion track associated with the higher energy TAM beam is more damaging than that Of the lower-range, 1.l!'J'-equivalent 276 MeV Br ion at BNL.

2) PMI LM139-- The SEE response of two PM I comparators to 196] MeV Xe resembles that of NSC. Transients have a more variable time durati -- 0.3 to 4 μs per pulse. Amplitudes are nearly rail-to rail at 22 to 26 V [] 'hoto 8]. A run with 600 MeV Ar [Photo 35] showed the same rail-lo-rail response as Xe, but a shorter duration Of 1.3 μs, equal to that of the NSC 1. M139.

Note that the low-LET thresholds [Table 3a] for this part differ greatly, depending O n output voltage (input polarit y.) This difference in response to input polarit y [at low 1.1 ET onl y] is seen again in the proton cress sections Of the NSC LM139 given in Tables 5 & 6.

3) NSC LM 11 I--- This comparator has an npn bipolar output transistor with 1.5 Kohm resi stor on the coll ector & grounded emitter. It thus has an entirely different S1 EE response from that Of the previ ous device types. When the comparator has a low output (an "on" transistor), the. transient causes the transistor to go Off for a time. For Xe, t he ampl it ude Of the output approaches -1 12V and lasts 0.1 to 0.4 ps [Photo 1 2]. Conversely, for a high output the "off" t ran si st Or is t urned on for a comparable period and the output approaches -J 5V [Photo 13]. The Ar (LET=7.3) run [Photo 36] showed a smaller amplitude of 2.5V and s] IOJ"(Cl' durati on Of ~0. J μs.

C. Op Amps

Three different bi polar op amps listed in Table J were tested at room temperature, with two different input voltage pairs clc.scribed in Table 4. [Note in the op amp test setup of Figure 2 that the.rc. is no voltage divider on the input for op amps. With the comparators, an op amp with gain = 0.5 was used 011 the output, and the numbers are corrected for that in thi s report and on photo capti ons.

In addition, a 1nanoF capacitor was installed on site, parallel to the J 00Kohm feedback resistors, in order to stop noise Oscillations. Post test, the op amp circuit was tested with a strobe light to compare the TAM configuration and a simplified con figuration. There was considerable difference in the two circuit respon ses, but none affecting the basic parameters of amplit ude and d urat ion.

Table 4. Input Polarity -- Op Amps

Positive input	0.5V into + input 0V into - input
Negative input	0V into + input +0.5V into - input

The data for the. op amps is different in form from comparator data. For Xe the am plitude ranges from 4 to 8V with a long pulse duration of -20 μs. For lo wer-LET Ar, the amplitude decreases, but the pulse width stays long. The trend with LET is similar to the variabi 1 i t y al nong transients observed for a fixed set of conditions. In this case, the amplitudes vary, but not the pulse widths.

Photos of Op Amp Response

1) LTN RH1056-- This rad hard bipolar op amp with gain = 12 has a JFET on the input. Input voltages Of] V and 0.5V (the. latter was a lest standard) did affect the amplitude, as seen in 1'11010s"

18 & 17, respectively], and a Change in input polarity caused a reversal in transit.nt polarity (not shown.) For 1961 MeV Xe [LET=44 MeV/(mg/cm^2)], the outputs have a smooth pulse shape, with 4 V to 8V amplitude, a very rapid rise time [<<1 µs] and a "1/e" decay time Of ~15 µs. With Ar (LET=7.3), the amplitude decreases to -IV [Photo 37], and the cress section decreases (see Table 3), but the pulse duration remains long. BNL data showed a LET threshold of 1,7 MeV/(mg/cm^2).

Again the TAM data can be compared to that taken with the lower energy Van (1e Graaff at BNL. In the BNL test, the cress section for a 276 MeV Br ion of LET=40 MeV/(mg/cm^2) was 9E-4 cm^2 compared to 1.41 E-3 cm^2 of Table 3 [both for S/N 2 175]. The increase **at** TAM may be real, but should be Of little consequence to project managers.

2) LTN LM 108 A-- It can be seen in photos 22 & 24 that this slower op amp [gain=10] has heavy-iOn induced transients having a slower rise time Of 2 µs. For this device type, the sign Of the input polarity has a significant impact on the amplitude and duration Of the transients. When irradiated with 1961 MeV Xe (LET=44), devices with a negative input [see definition in Table 4] are much more susceptible than those with positive input. Negative-input devices [Photo 24] exhibit a great variability in transient amplitudes ranging, up to 13V and a "1/e" decay time of 14 µs; positive-input devices [Photo 22] have a fairly consistent (±20 %) 5V amplitude and 10 µs "1/e" decay time. With Ar (LET=7.3), the amplitude and pulse duration remain the. same. for the positive-input (+0.5V) device [Photo 39]; no data were obtainable for a cross section. BNL data showed a LET threshold of <1.45 MeV/(mg/cm^2).

3) LTN RH 108A-- 'There is no significant difference between the response of this device type and tile LTN LM 108A. Whatever means were used to obtain the rad hard (RH) prefix did not affect the SEE transient response.

IV. *Proton Experimental Results*

The first observations **of** proton-induced single event transients were obtained at the Indiana University Cyclotron Facility (IUCF) for the same NSC LM139 comparator tested with heavy ions. This result was expected because of the low LET thresholds for the heavy ions transients.

Three devices were tested at room temperature, using the same setup used for the TAM test with heavy ions. The devices **were** irradiated with 200 MeV and lower energy protons. The preponderance **of** data was taken with ±25 mV input (at the part) with power supply voltages of ±15V. Note that the applied voltage differentials are twice the voltages at the part, because of a divide-by-two circuit on the. input (See Figure 1). The cross sections, defined as the number of transients per unit fluence exceeding a 2V output trigger voltage, are summarized in "Table. 5 for the postive and negative 25 mV data. The difference in cross sections for the two input voltage polarities is significant.

Table 5. LM139 Transient Cross Section (cm^2 per device) for 200" MeV Protons

S/N	+25mV	-25mV
2172	2.2E-11	1.6 E-10
2173	4.5 E-11	7 E-11
2174	3 E-11	1.4 E-10

All **three** parts were also tested at lower proton energies Ep **of 120**, 90, 60 and 30 MeV. However, no transients were induced for these lower energy **protons** with inputs of +25 mV. For the data shown in "Table 6, the input voltages are ±12.5 mV. Again, the cross sections differ for the two polarities. Note also that the cross section for the 200 MeV proton can be compared with the entry in '1'able 5 for ±25 mV; the cress secti ons for the lower input voltages of Table 6 are about an O]"(IC1" of magnitude larger than those in Table 5. This observation leads to the test objective displayed in Table 7. '1'here, two parts were tested with 2oo MeV protons Only, but for Several different input voltages-- in order to locate a high voltage differential voltage threshold above which no proton SEE transients are observed. The data are statistically meager, so d ata for the two parts are combined. This threshold is approximately found. The fact that the transients are certain to be small as we approach threshold was relevant and useful.

Table 6. Low Energy Proton Cross Sections (cm^2 per device) vs. E_p

Ep (MeV)	S/N	+12.5 mV	-12.5 mV
200	2172	2 E-10	2..8 E-9
120	2172	5 E-11	9 E-10
90	2172	1.4 E-10	1.1 ii-9
60	2172	2 E-11	1.2 ii-9
	2173		<5 E-11
	2174	4 E-11	3.5 E-10
30	2172	<2 E-11	2 E-10
	2173	<2 E- 11]	<5 E-11
	2174	<211-11]	2.5 E-10

Diagnostic Runs

Finally, a few diagnostic runs were directed at an empty socket with a total large fluence Of>]012 protons/cm^2 (200 MeV) to allay suspicions that the device measurements are noise. '1'here Were no Upsets Of the empty Sockets, which should disprove the noise hypothesis.

Other diagnostic 1"1111S were taken by reirradiating parts with the same conditions as they experienced before receiving the total accumulated dose. '1'here are indications that the dose accumulations (- 100 Krads) affect the SEE data adversel y.

Statistics

The statistic s are sparse throughout, because a high proton fluence (corresponding to a high total dose) was required to induce transients. This, of course, is good news for space projects--bad news for statisticians. It is possible to establish Poisson confidence limits fOr the data by going through the raw data. Such an exercise might be warranted with this data, only if flight confidence limits are sought.

Table 7. Cross Sections Vs Input Gap

Gap (mV)	Cross section (cm^2)	Note
+ 500	0 1<51;-121	
+ 50	7 E-12	Small*
-50	2 E-11	
-62.5	7 E-12	
-75	5 E-12	Small*
-100	0 [< 1 E-1]**	

* "Small " means tha only transients Of a few volts are observed for the noted test condition.
** The fluence s]1011]() have been taken to 1 E 12 protons/cm^2.

Photos of Proton-Induced Transients

As with heavy ion data, the true device voltage is twice that shown on the scope, because Of a divide-by-two circuit on the output. Thus maximum device voltage swings fOr the comparator are -26 volts or nearly rail-to-rail, and the smallest detected device output swings of 2V are established by the choice of a 1 V scope setting on the circuit output. References in the text are for the true device voltage. Volt amplitudes are the vertical axis; time scales horizontal.

Note that differences between the individual proton responses of a comparator arc characteristically manifested by differences in both the duration and amplitude--in distinction to changes mainly in lime durati on seen in heavy ion tests of comparators. Small amplitudes of the comparators can also occur when test conditi ons approach a threshold appropriate to the selected input voltage gap and proton energy.

This qualitative difference with protons can be attributed to the wide di fferences in deposited energy from nuclear reaction products induced by a proton of a given energy. Geometric considerations play a role, but so does the energy spectrum Of recoil sil icon at oms.

Proton P5 and P6 arc for 200" MeV protons with a positive and negative input of 25mV, showing rail-to-rail amplitudes of opposite polarity and 200 nsec widths. Photo P8 displays tbc t i me wid t b bet ter for a diffc.rent scope sweep rate. (200 nsec per divi sion.)

A second part was irradiated with 200 MeV prot ons and showed a si m i i ar response. Additional data with an input gap of +12.5 mV were obtained. The smal ler input voltage does not affect the shape of the transient, but it has a larger cross section.

Data for a third part supports previous data. In addition photo 1'18 for -12.5 mV shows a wide range of amplitudes and widths. Photo P1 9 for -3 ' 7 . 5 m V moves toward the input voltage threshold. Wc see a diminished amplitude and width, as expected.

All three parts arc tested with lower proton energies, as shown in Table 6. Photo 1'35 for 200 MeV protons shows a much wider transient -- approaching 1 µs -- attrib uted to an acc u1 nulated de positi on (dose) of protons late in the test campaign. Wc also s c c that 30 Mc V prot ons are incapable of generating rail -to-rail voltages in photo P36.

The ph otos in support of Table 7 (not s]1owJ1) demonstrate that larger absol ute magnitudes of input voltages for either polarity correspond to smaller output transients, as expected.

Proton Summary

The NSC LM139 comparator is susceptible to protons having energies typical of flares and the Van Allen belts (30 to 200 MeV.) Th e cross sections are consistently higher for tbc negative applied input as defined in section 111-11, just as with heavy ions. The cress secti ons get smaller and ultimately vanish at lower proton energies and at higher input voltage di fferentials. The transient can be a rail-to-rail excursion that lakes place in -200 nanosec 01 longer. The data obtai ned here are sufficient to permit a rate estimate for a known proton environment (fluence vs. energy) and specified voltage gap.

The trend s of thi s data, plus a diagnostic test, confirm that this is a single event effect. The respon se ari ses from prot [)1) interaction with lattice nuclei leading to ionizing radiation deposition from the reaction products.

V. Conclusions

The reported transients from troth heavy ions and protons may be a major threat to some space and satellite subsystem s. System personnel will have to take a close look at]1ow transients, as summari zed below, are likely to impact adjacent electronics. Tbc heavy ion transients have very bad vital signs:

(1) LET threshold <2 MeV/(mg/cm^2)
(2) Large amplitudes (many volts)
(3) Long duration (0. 1to 20 µs.)

The proton transients are also dangerous:

(1) Proton energy threshold of ~30 MeV at input gap of 12.5 mV; higher energy thresholds for higher gaps.
(2) Amplitudes that can go rail-to-rail.
(3) Durations approaching 1 µs.

References

(1) R. Koga, S. D. Pinkerton, S. C. Moss, D. C. Mayer, S. LaLumondiere, S. J. Hansel, K. B. Crawford & W. R. Crain, "observation of SEUs in Analog Microcircuits," IEEE Trans. on Nuc. Sci, NS-40, No. 6, 1838 (Dec., 1993)

(2) R. Ecoffet, s. Duzellier, P. Tastet, C. Aicardi, M. LaBrunee, "Observation of Heavy Ion Induced Transients in Linear Circuits," 1994 IEEE Radiation Effects Data Workshop, p.72 (Dec., 1994)

Captions for Heavy Ion Photos

Photo 2. Transient of NSC LM139 comparators with xc [LET=44 MeV/(mg/cm^2).] 4V per vertical division; 0.5 µs per horizontal div.

1'1)[)(05. Same as Photo 2 with reversed input. Note reversed output transients.

Photo 34. NSC LM139 tested with lower LET 600 MeV Ar [LET=7.3] . Note shorter pulse width than with Xc. 4V/div.; 0.5 µs/div.

1'110108. Representative transient Of I'MI LM139 comparator with Xc (LET=44). 4V/div; 0.5 µs/div.

Photo 35. I'MI LM 139 tested with lower LET 600" MeV Ar [LET=7.3] . Note shorter pulse width than with Xc. 4V/div; 0.5 µs/div.

Photo 12. NSC LM 111 for Xc. Low output from bipolar transistor. 4V/div.; 0.2 µs/div.

Photo 13. NSC LM111 for Xc. High transistor output. 4V/div; 0.2 µs/div.

Photo 36. NSC LM 111 for Ar. Low transistor output. 1 V/div; 0.2 µs/div

Photos 17 & 18. LTNRH1056 fOJ' Xc. A comparison of two different input voltages (reversed). Photo 17 is 0.5V; photo 18 is IV. 2V/div; 5 µs/div.

Photo 37. LTNRH1056 for Ar. Same voltage Scales as for 1'11010s 17 & 18.

Photo 22 & 24. LTN LM108A for Xc. A comparison of positive and negative input shows a significant difference in output. 2V/div; 2 µs/div.

Photo 39. LTN LM 108A for Ar. Smaller voltage = ().5 V/div; 2 µs/div.

Captions for Proton Runs

Photo P5. Transient of NSC LM139 comparator with 25 mV input gap & 200" McV protons. 4V vertical division [at {ic.vice]; 2 microsec per horizontal.

Photo 1'6, Similar to Run 5 with reversed input. Note reverse.ci output transient.

Photo 1'8, Same conditions as Run 6 with 200 nanosec/horizontal division.

Photo P18. Transient of NSC LM 139 for -12.5 mV input gap& 200 MeV protons. **4V** vertical; 200 ns horizontal .

Photo P19. Same as Run **18**, except for -37.5 mV input gap. Note a diminished amplitude and width.

Photo P35. Transient for -12.5 mV input gap & 200 MeV protons taken after 1 ()() Krads. 4V vertical; 200 ns horizontal. Note longer transients than for Run 18.

Photo P36. Transient for -12.5 mV & 30 MeV protons

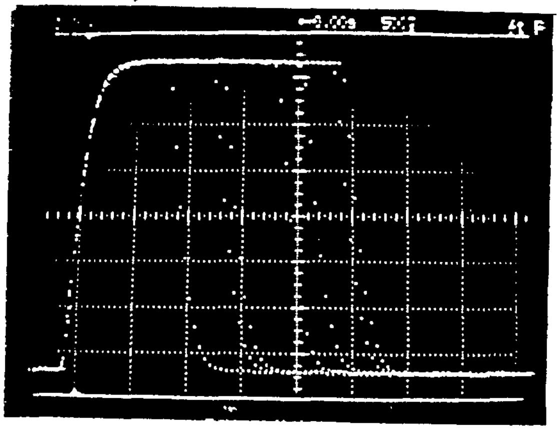

Photo 2. Representative transient of three NSC LM139 comparators with Xe [LET= 44 MeV/(mg/cm^2).] 4V per vertical division; 0.5 microsec/horizontal div.

Photo 5. Same as Photo 2 with reversed input. Note reversed output transients

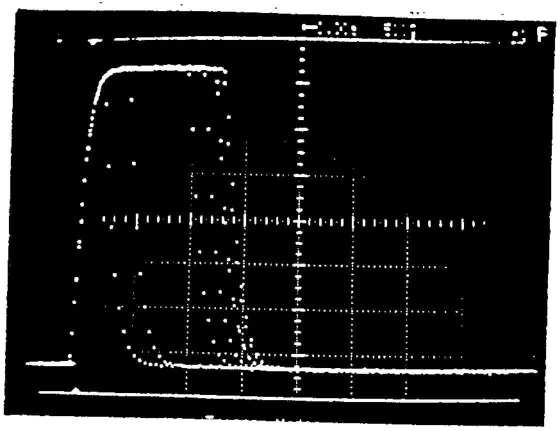

Photo 34. NSC LM139 tested with lower LET 600 MeV Ar [LET=7.3] Note shorter pulse width than with Xe. 4V/div; 0,5 microsec/div.