ESA-QCA00122S-N98

Heavy-ion Study of Single Event Effects in 12- and 16-Bit ADCs

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Abstract

Results of a research program to evaluate heavy ion single event effects in 12- and 16-bit ADCs are presented. The devices studied were the AD676, AD7884 and AD7893. Transient and "lingering" errors were found as well as bit flips and a temporary latch-up phenomenon. Implications for test methodologies are discussed.

I. INTRODUCTION

Several recent studies [1-8] have demonstrated the existence of single event effects (SEE) in analog-to-digital converters (ADCs), caused by the impact of heavy-ions, cosmic rays and protons. A straight-forward effect is the generation of a transient charge or voltage pulse which in turn produces an incorrect digital output code - but which lasts for only one data conversion. However in addition to these transient "noise" events, other effects can occur if the ion strikes the digital calibration or control circuitry which is used in many state-of-the-art high speed/high precision ADCs. In this case long-lived (or "lingering") errors can be produced which last for several conversions, or sometimes until an ADC re-calibration or a power off/on occurs. Such events form a subset of the single event functional interrupt (SEFI) seen in many analog or mixed signal circuits, as discussed by Koga [9] and will clearly have important consequences for the operation of spacecraft payloads and systems.

As well as a trend to use increasingly more complex ADC architectures, there is also a demand to minimize power consumption and use CMOS or BiCMOS rather than bipolar parts. A well known effect in CMOS circuits is single event latch-up (SEL) [10] which produces a large increase in supply current until power is cycled. However, less easily detected "mini-latch" events can be observed in some complex circuits, ADCs included.

In this paper, we discuss effects in Analog Devices AD7893 and AD7884 and extend the work of LaBel et al [1] and Wilson and Dorn [2] on the AD676 (Ref [2] reports on the AD677 which is a parallel output version of the AD676). It will be seen that the AD676, which has a digital control die, exhibits surprising "lingering" errors whereas the AD7884 and AD7893 do not. Data are presented for a range of LETs and compared with previous results obtained with ^{252}Cf fission fragments [11].

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Several approaches can be adopted for ADC testing, depending on the precision and conversion time of the device and the parameters of most importance to the user. In this work, the use of a custom-designed DSP-based data collection system [11] made it possible to measure both the magnitude of the data conversion errors and the ADC codes at which they occurred. Also, both static and dynamic (saw-tooth) input signals could be applied to the ADC. It will be seen that effects can be dependent on the type of input signal used. This needs to be taken into account when devising test methodologies for ADCs.

II. EXPERIMENTAL

Testing was performed on de-lidded device samples using the heavy ion irradiation facility (HIF) of The Université Catholique de Louvain-la-Neuve, Belgium [12]. The devices tested were the 12 bit AD7893SQ and the 16 bit AD7884AQ and AD676AD, which are all ceramic DIL packaged and manufactured by Analog Devices Inc. The device markings for the samples tested are given in table 2.

Table 1 A summary of the devices tested. All the devices were manufactured by Analog Devices Inc.

ADC	Technology	Architecture
AD676AD 16 Bits	Digital control die: Analog Devices' DSP CMOS process Analog die: Bi-MOS II	Parallel interface, successive approximation, 10μs convert time.
AD7884AQ 16 Bits	LC^{2}MOS- Linear compatible CMOS (Precision bipolar circuits with CMOS logic).	Two pass flash, 5.3μs conversion time.
AD7893SQ 12 Bits	LC^{2}MOS	Serial interface, successive approx, 5.5μs convert time.

Using the HIF, heavy ions can be provided with an LET range of 0.4 to 55.9 MeV cm^2/mg at normal incidence; and higher if the Device Under Test (DUT) is tilted. The range in silicon of all the available heavy ion species at CYCLONE is between 42 and 130μm. Figure 1 shows the LET at normal incidence for the ions used in this study. Also shown for comparison are the LET obtained with the ^{252}Cf fission fragments used previously [11]. For all ions the incident flux at the DUT surface can range from a few particles cm^{-2} s^{-1} to 1x10^6 cm^{-2} s^{-1}. Beam uniformity was within ±10% over the 25 mm diameter of the beam profile.

Table 2 Device markings

Sample	Internal Marking	External Marking
AD676AD		
B	18766, 1991 digital die A18701 R1 analog die	9205 TK9083
C	B18701 1996 digital die A18766 1992 analog die	9703 B54434
D,E	as C	9702 B54233
AD7884AQ		
A	none	9323 OF26184.1
C	none	9405 OF 32157.1
AD7893SQ		
C	AD M BV	9446 67252 83868 C

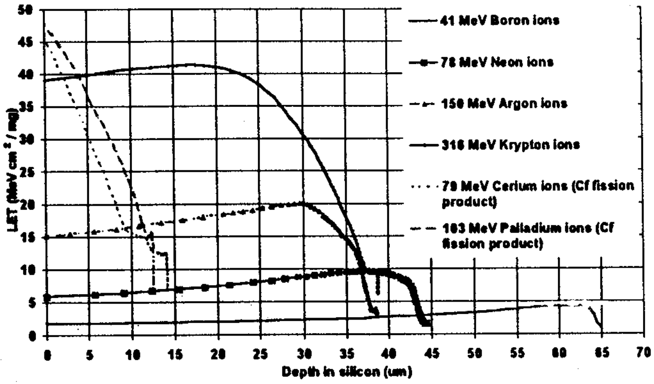

Figure 1 LET versus depth in silicon for the heavy ions used (data from [13]). For the two main Californium-252 fission products (cerium and palladium ions) the LET varies rapidly with depth.

The test equipment is shown in Figure 2. Each device under test, (ADC, DAC or amplifier) can be mounted in a dedicated daughter board interfaced to a analog motherboard containing a saw-tooth wave form generator, multiplexers, buffers and interface drivers and receivers. The analog motherboard is connected via a custom designed data memory board with four 64 Kword, 32 bit deep arrays to an Analog Devices' 32 bit DSP ADSP-21020 EZ-Lab evaluation board with 30 ns instruction cycle time. This DSP system allowed high speed acquisition of ADC data. Further details are given in [11].

Two separate software routines were used for data collection. The first was used for testing with a static (0V) voltage input and the second when using the dynamic (saw-tooth) input. In both cases, ADC conversions were stored in real time in a frequency histogram of the number of conversions per output bin (ADC code). For static testing this yielded the distribution of transient errors. When testing with a saw-tooth input, the corresponding histogram of ADC conversions per output bin yields the differential non-linearity (DNL), which can be affected by single event errors. However measuring the transient event distribution with saw-tooth testing needs the difference between the ADC converted value and the expected ADC converted value (calculated in real time during the test [11]) to be recorded in a separate frequency histogram. In this study, *both* the actual value of the ADC conversion and the corresponding expected value were recorded if the difference between the ADC converted value and the expected value differed by more than ±15 bins. In this way both the errors and the ADC values at which they occurred could be determined. In addition, the approximate time at which events occurred during the saw-tooth input test were recorded. (this is important for detecting lingering errors).

Under control (un-irradiated) conditions the standard deviation of the ground input histograms for each of the AD676, AD7884 and AD7893 samples tested was consistently measured to be of the order of 1 Least Significant Bit (LSB).

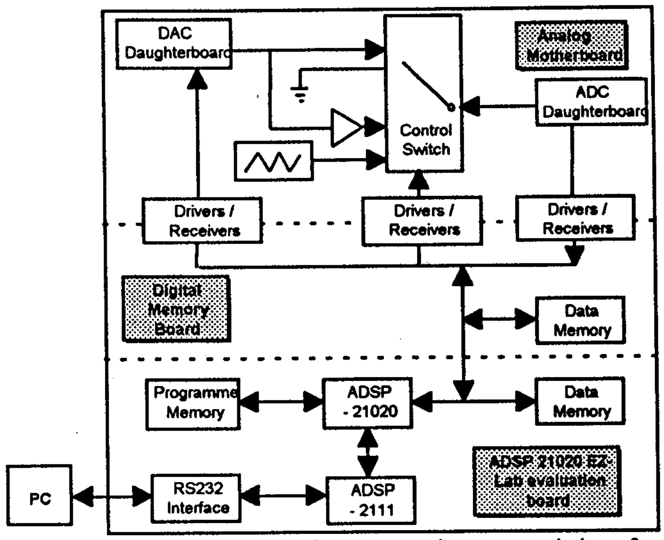

Figure 2 Schematic diagram of the test equipment consisting of an analog motherboard, custom designed digital memory board, ADSP 21020 EZ-Lab evaluation board and a personal computer.

III. RESULTS

As far as the authors are aware, the AD7893 and AD7884 have not been previously tested for SEE under heavy ion irradiation. Results for the AD676 have been reported by LaBel et al [1] and for the AD677 (a parallel output version of the AD676) by Wilson and Dorn in [2]. The latter saw 'lingering errors' due to single event upsets in the digital die of the AD677. Sharma and Sahu have recently given total ionizing dose data for the AD677 [14].

A. AD676AD (16 bit ADC)

The AD676AD package contains two die; one analog and the other a digital control circuit. AD676 performance is optimized by correction of internal non-linearity by the digital die auto-calibration circuit which applies a correction factor to the ADC output from the digital die RAM. Data was collected for whole AD676 irradiation and for isolated irradiation of the digital and analog circuits. Five AD676 device samples were available, labeled A to E. Sample A was retained as an un-irradiated reference sample and B to E were used for heavy ion irradiation testing.

Whole AD676 Irradiation

The AD676 under whole chip irradiation showed three types of heavy ion induced single event effect. The first was the classic temporary data conversion error, or transient upset. The second effect was the lingering error, of which we distinguish between two types (though the distinction between them is somewhat subtle and may be due more to the methods used in analyzing the data than to fundamentally different mechanisms). In the first type the ADC became jammed, repeatedly outputting the same value (± a few LSB of noise) regardless of the analog input. The second kind was the 'bit-flip' where values continued to be converted by the ADC, but to an incorrect value which was shifted by the magnitude of a bit transition level, again plus the usual background noise. Both kinds of lingering error ('jam' and 'bit-flip') could be resolved by initiating a re-calibration of the ADC.

The transient and lingering errors occurred for all the LET values used (from 1.7 to 28.2 MeV cm^2/mg) but at the highest LET there was a tendency for the third type of error - this time 'semi-permanent' - to occur. Normal operation could only then resume after a power off/on cycle. The 'semi-permanent' errors were again of two types: 'jam' errors (as before but not affected by a re-calibration) and excess noise that resulted in transient errors, even when the device was not being irradiated. After a 'semi-permanent error' the AD676 samples were not observed to draw any excess current. The highest LET for which these errors did not occur was 19.94 MeV cm^2/mg, so this can be taken as the threshold LET for these effects. Testing at higher incident LET and fluence was not pursued since LaBel et al [1] had observed single event latch-up in the AD676 at an LET of 25.0 MeV cm^2/mg and fluence $1x10^7$ cm^{-2} and it was considered undesirable to risk permanently damaging a device since few samples were available. In this study, single event latch-up was not observed in the two AD676 samples under irradiation at 28.20 MeV cm^2/mg (the highest LET used) and fluence $1x10^6$ cm^{-2}.

The various effects are illustrated below. Figures 3, 4 and 5 show transient events from ground input tests obtained for the same AD676 device (sample E). Under control (un-irradiated) conditions ADC conversions were only observed to occur in ADC output bins between -12 and +15. At low LET (1.70 MeV cm^2/mg) it can be seen that the upset events are of a lower magnitude than observed at higher LET (3.40 and 5.85 MeV cm^2/mg).

Transient, lingering, and semi-permanent errors were seen in saw-tooth tests (as mentioned above, the latter only at 28.2 MeV cm^2/mg) and these are illustrated in figures 6, 7 and 8, for which the actual and expected ADC output was collected every time the error was more than 15 LSB. The test software was arranged to automatically start an ADC re-calibration after every 10 errors (regardless of the time at which they occurred). Hence a 'lingering' error is noticeable by the presence of 10 consecutive errors . The logarithmic plot (figure 7) shows that there is some noise on the 'lingering error' outputs.

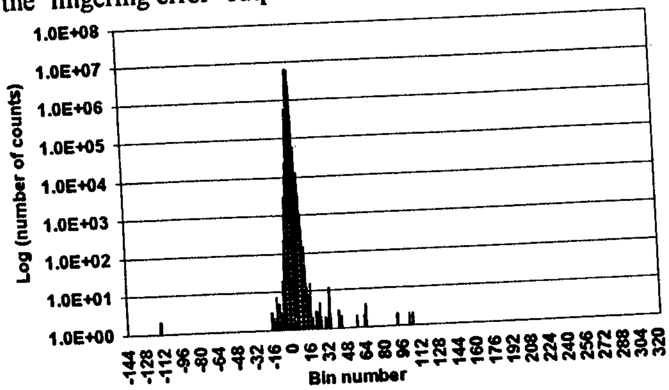

Figure 3 Ground input test histogram recorded for whole AD676 irradiation with boron ions at normal incidence. Approximately 50 million conversions were recorded under an incident flux of $3.6x10^3$ cm^{-2} s^{-1}, fluence of $1x10^6$ cm^{-2} and LET of 1.70 MeV cm^2/mg. 183 upset events were observed between bins -409 and +274. Conversions within the control data range of bins -12 to +15 were not included as heavy ion induced upset events.

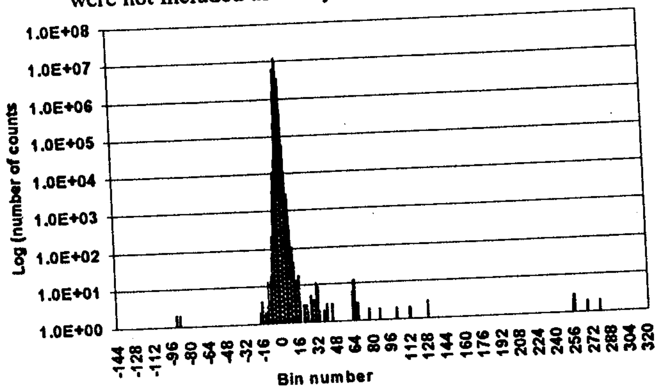

Figure 4 As figure 5, but with boron ions at 60 degrees incidence. Approximately 92 million conversions were recorded under an incident flux of $2.0x10^3$ cm^{-2} s^{-1}, fluence of $1x10^6$ cm^{-2} and effective LET of 3.40 MeV cm^2/mg. 230 upset events were observed between bins -539 and +604.

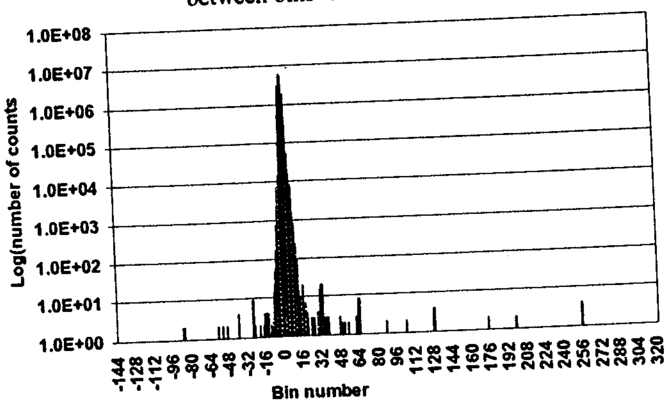

Figure 5 As figures 4 and 5, but with neon ions at normal incidence. Approximately 43 million conversions were recorded under an incident flux of $4.8x10^3$ cm^{-2} s^{-1}, fluence of $1x10^6$ cm^{-2} and LET of 5.85 MeV cm^2/mg. 278 upset events were observed between bins -1140 and +1160.

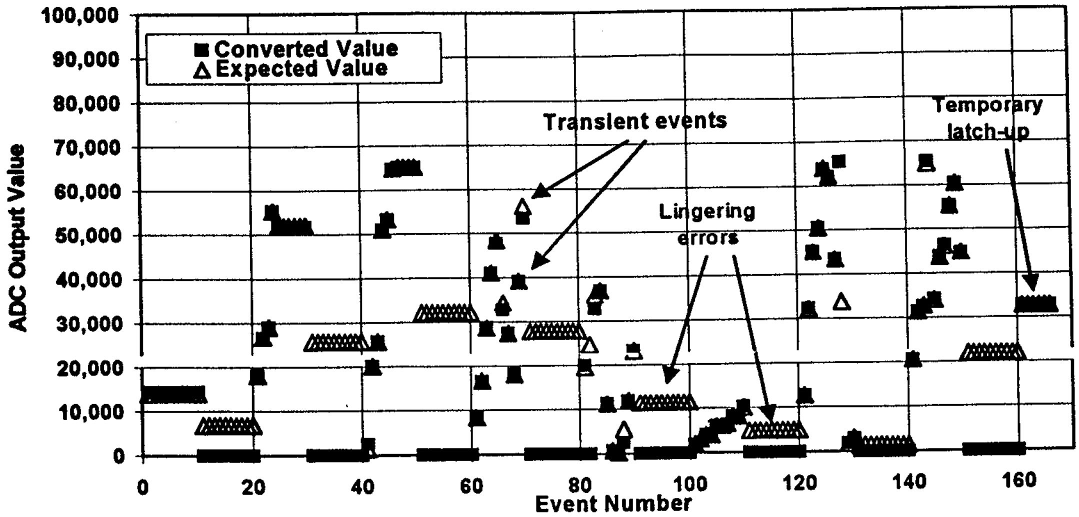

Figure 6 The ADC converted value plotted against the upset event number for the AD676 sample C, under irradiation with argon ions at an LET of 28.20 MeV cm^2/mg. The incident flux was $1.5x10^3$ cm^{-2} s^{-1} and the fluence $1x10^6$ cm^{-2}.

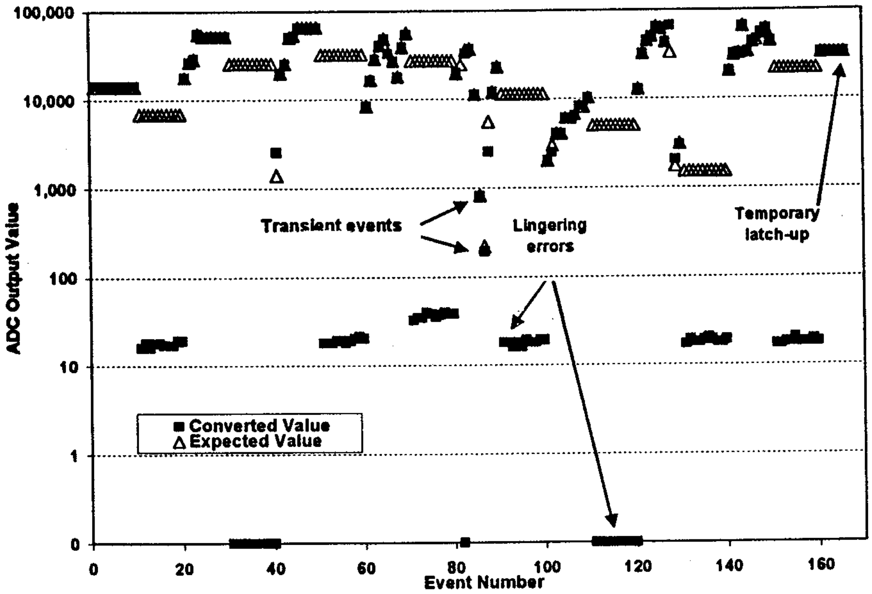

Figure 7 Same data as figure 6, but on a logarithmic scale.

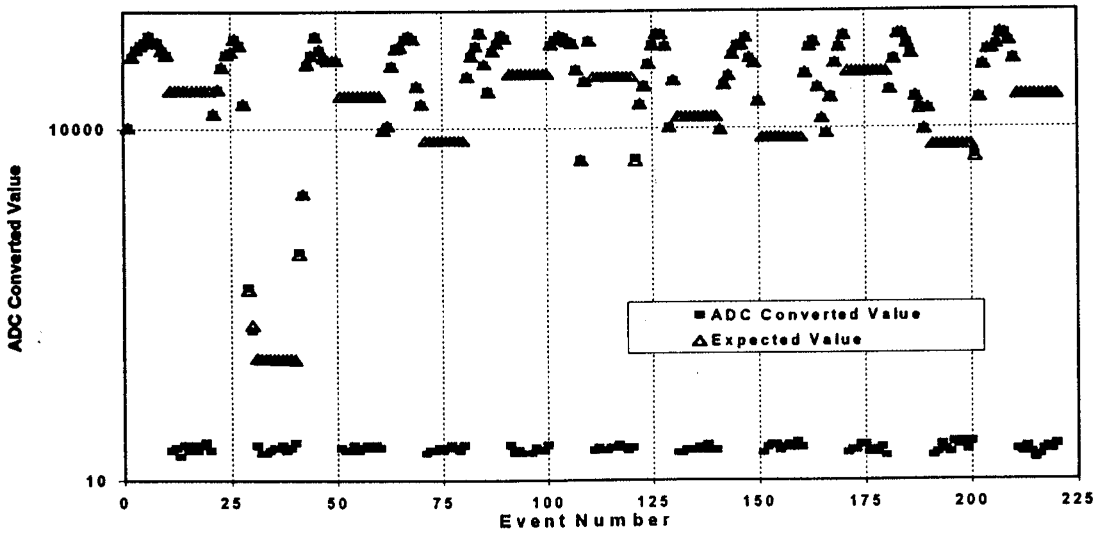

Figure 8 The ADC converted value plotted against the upset event number for the AD676 sample E, under irradiation with boron ions at an LET of 1.70 MeV cm^2/mg. The incident flux was $3.5x10^3$ cm^{-2} s^{-1} and the fluence $1x10^6$ cm^{-2}.

indicated by the clusters of events at bit transition levels in Figures 9-11. These show histograms of the difference between actual and expected values for all the ADC conversions. As mentioned above, the distinction between a 'bit-flip' and a 'jam' error is somewhat tentative. The 'bit-flip' was a small error (only a few LSB) and was seen in both ground and saw-tooth testing. The converted value was the expected one but offset by a constant amount (the value of the bit which is flipped). The 'jam error' tended to be larger in magnitude and was not seen in the static ground tests. Though, if static tests had been performed with different voltage inputs (over the range 0V to full scale input), instead of just at 0V as performed in this study, the 'jam' might then have been seen. The 'jam' produced an output which did not follow the saw-tooth. The output was not the expected conversion with a bit-flip error, but rather a psuedo-constant value, with some noise.

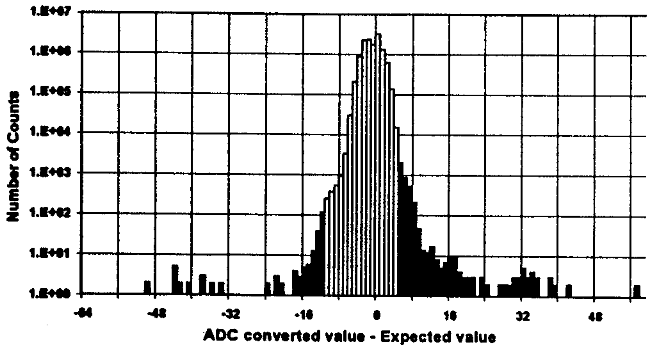

Figure 9 Histogram of the difference between actual and expected values for AD676 sample D with argon ions at normal incidence and effective LET 14.10 MeV cm^2/mg. Incident flux $2.3x10^3$ cm^{-2} s^{-1}, fluence $1x10^6$ cm^{-2}. The light shaded bins show the control (unirradiated) data range, (bins -11 to +6).

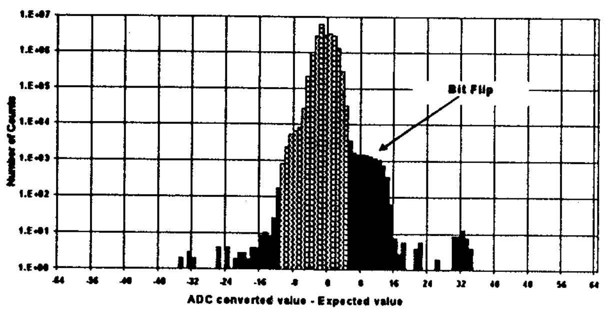

Figure 10 As figure 9, but with argon ions at 45° incidence and effective LET 19.94 MeV cm^2/mg. The incident flux was $1.5x10^3$ cm^{-2} s^{-1} and the fluence $1x10^6$ cm^{-2}.

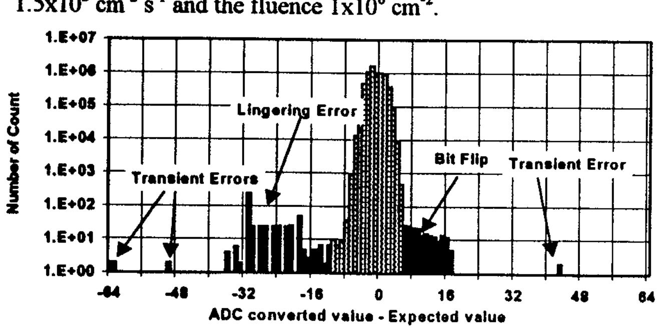

Figure 11. As Figures 9 and 10, but with argon ions at 60° incidence and effective LET 28.2 MeV cm^2/mg. Flux $0.9x10^3$ cm^{-2} s^{-1}, fluence $0.2x10^6$ cm^{-2}.

separately for both transient and lingering 'jam' errors (Figures 12 and 13, respectively). The transient upset event cross section was measured to be of the order of 10^{-4} cm^2/device and the 'jam' error cross section was the order of 10^{-4} to 10^{-3} cm^2/device. In both cases the threshold cross section was very low at less than 1.70 MeV cm^2/mg. When the AD676 was previously tested [11] with ions from a ^{252}Cf source with LET in the range of 42 to 45 MeV cm^2/mg and fluence $5.0x10^4$ cm^{-2}, the transient event cross section was measured to be $(1.7\pm0.2)x10^{-3}$ cm^2/device. This cross section may however be artificially high for the earlier ^{252}Cf tests because of the detection thresholds used and contamination by bit-flip errors.

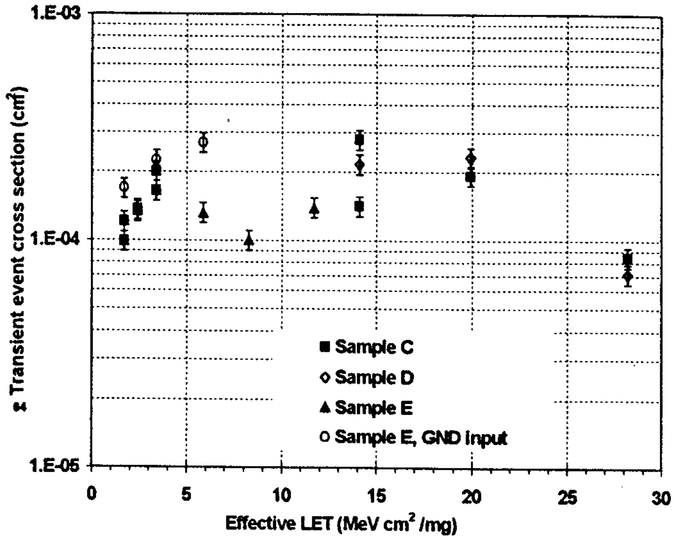

Figure 12 Transient event cross sections obtained using a saw-tooth input for the AD676. Only transient upset events > ±15 bins from their expected value are shown.

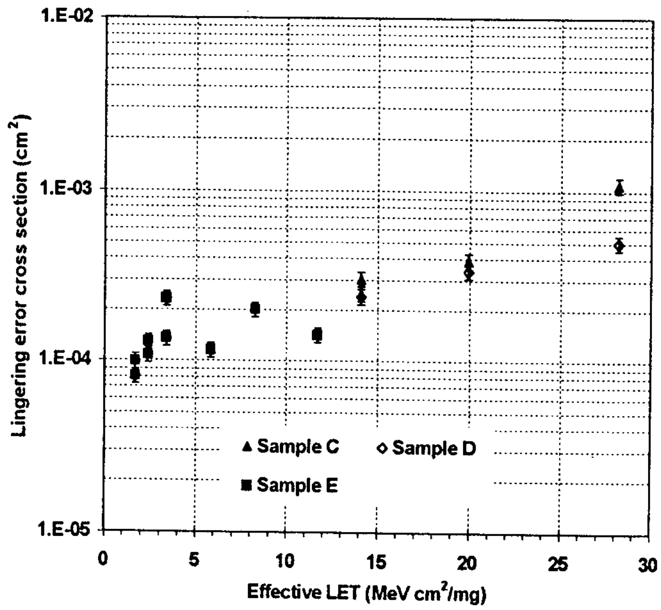

Figure 13 Lingering 'jam' error event cross section data plotted for the AD676, under whole chip irradiation with heavy ions. All the data were recorded using a saw-tooth input.

Digital AD676 die irradiation

Two ground input tests were made where the analog die of the AD676 was shielded from the incident neon ions and only the digital die exposed. Data is shown in Figures 14 and 15.

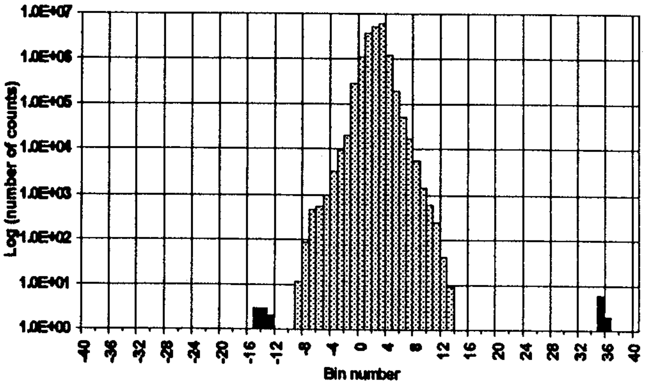

Figure 14 Ground input histogram recorded for digital chip irradiation with neon ions at normal incidence for the AD676 sample E. Conversions recorded under control conditions all occurred between bins -12 to +15 inclusive, (light shaded bins). The incident flux was $4.3x10^3$ cm^{-2} s^{-1} and fluence $1x10^6$ cm^{-2}. Twenty transient upsets were observed during the course of the test in bins outside the control range. Only two of these are not illustrated, one event in bin +128 and one in bin +1166.

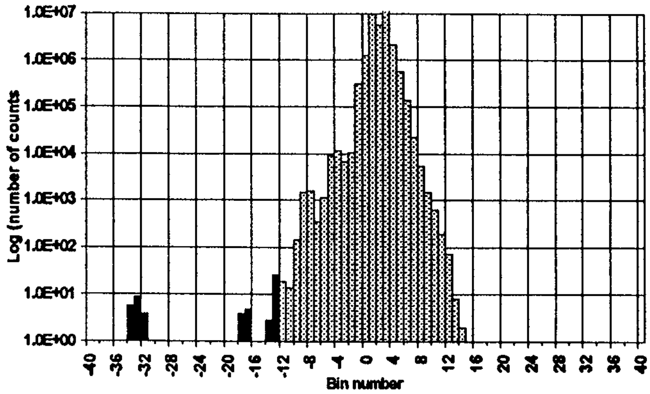

Figure 10 As figure 14, but with neon ions at 60 degrees incidence. The incident flux was $2.0x10^3$ cm^{-2} s^{-1} and the fluence $1x10^6$ cm^{-2}. Sixty transient upset events were observed during the course of the test. Only one upset event is not illustrated here which occurred in bin -852. Saw-tooth input test measurements were also made for isolated irradiation of the digital die of the AD676 sample E with boron and neon ions of effective LET 1.70 to 11.70 MeV cm^2/mg.

Comparing Figures 16 and 17 with Figures 6-8, it can clearly be seen that the digital die of the AD676 is more susceptible to lingering errors rather than transient upset events. Figure 18 illustrates the upset event cross section which was calculated separately for lingering and transient upset events for the digital die of the AD676.

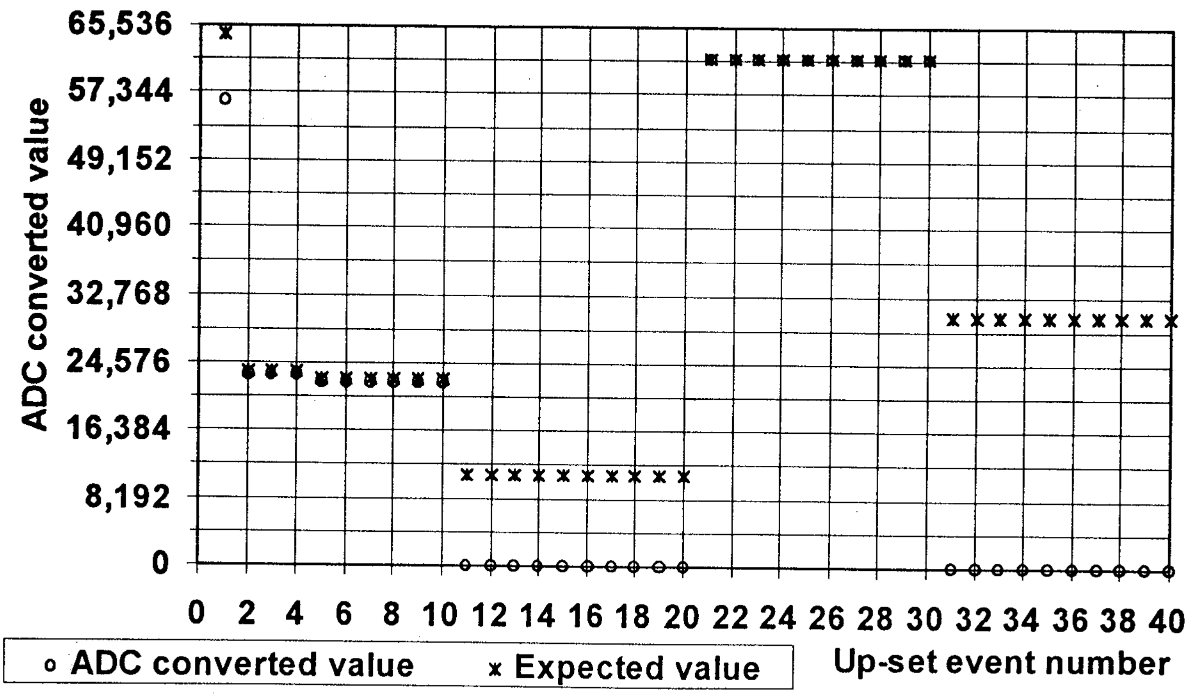

Figure 16 ADC converted value and expected value plotted against the upset event number for digital die irradiation of the AD676 sample E. The digital die was irradiated with neon ions at normal incidence yielding an LET of 5.85 MeV cm^2/mg. The incident flux was $0.6x10^3$ cm^{-2} s^{-1} and the total fluence $0.6x10^3$ cm^{-2}. Only conversions greater than ±15 units from the expected converted value are plotted here.

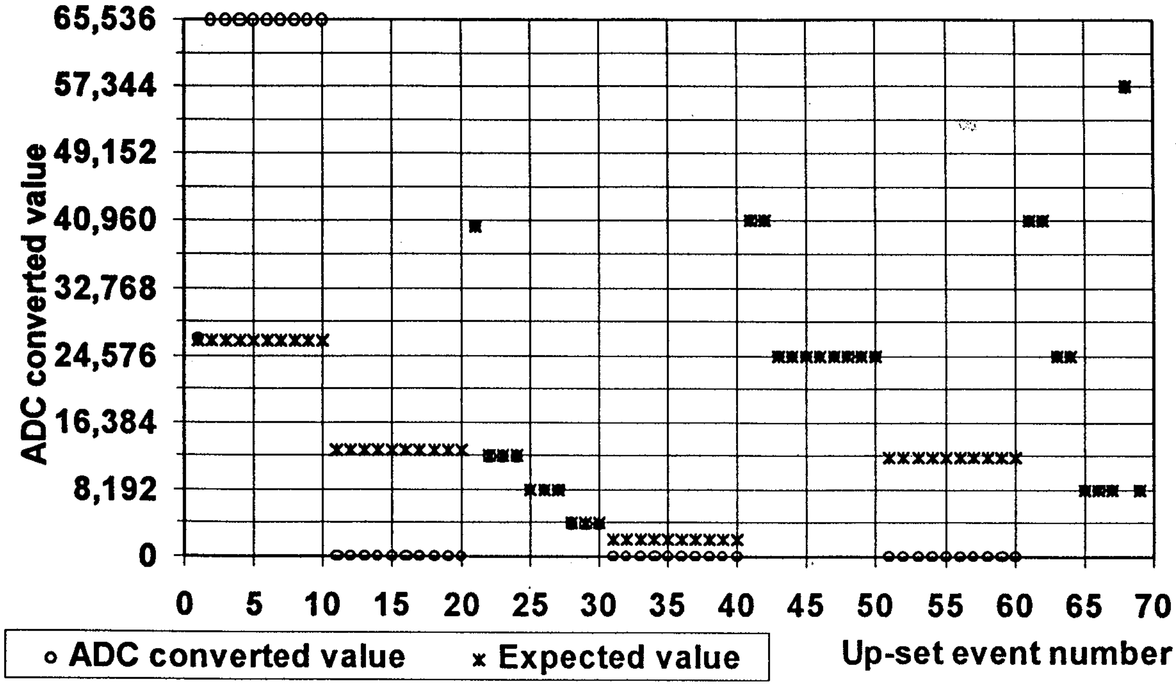

Figure 17 As figure 16. The incident flux was $4.6x10^3$ cm^{-2} s^{-1} and the fluence $1x10^6$ cm^{-2}. Only upset events greater than ±15 units from the expected converted value are plotted here.

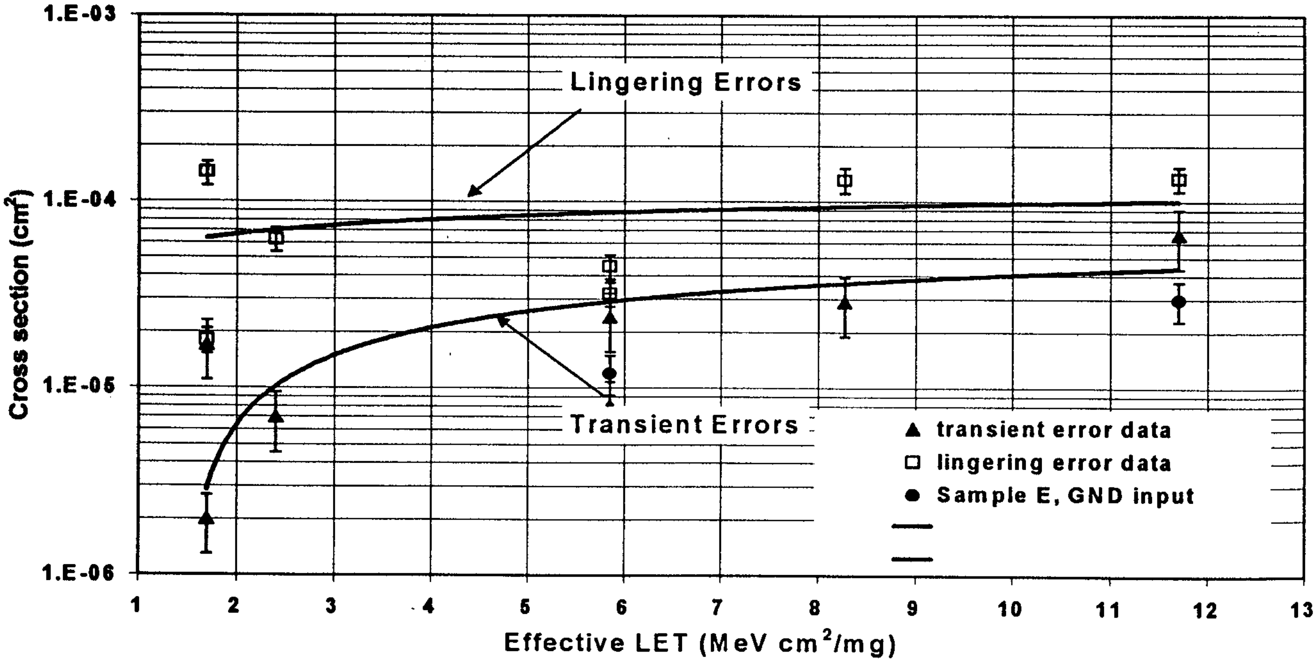

Figure 18 The upset cross section curve plotted for both transient (solid triangles) and lingering errors (hollow squares) recorded during the irradiation of the digital chip of the AD676 sample E using a saw-tooth input. Ground input data points are illustrated with solid circles. (It was not possible to separate lingering and transient errors in this case).

Analog AD676 die irradiation

Using saw-tooth input tests (ground input was not used), the analog die was found to be only susceptible to transient error events. No lingering errors or temporary latch-up phenomena were observed. The cross section for transients was (4.2±0.5) $x10^{-4}$ $/cm^2$ for LETs in the range used (5.85 to 8.27 MeV cm^2/mg).

B. The 16 bit AD7884AQ

Four ground input irradiation tests were carried out using AD7884 sample B under irradiation at effective LET between 5.85 and 34.0 MeV cm^2/mg, (see Figures 19-21). As the incident ion LET increased, so the magnitude of the upset events observed also increased. However, events were consistently recorded in certain bins over the four separate tests that were carried out. As illustrated in figure 22.

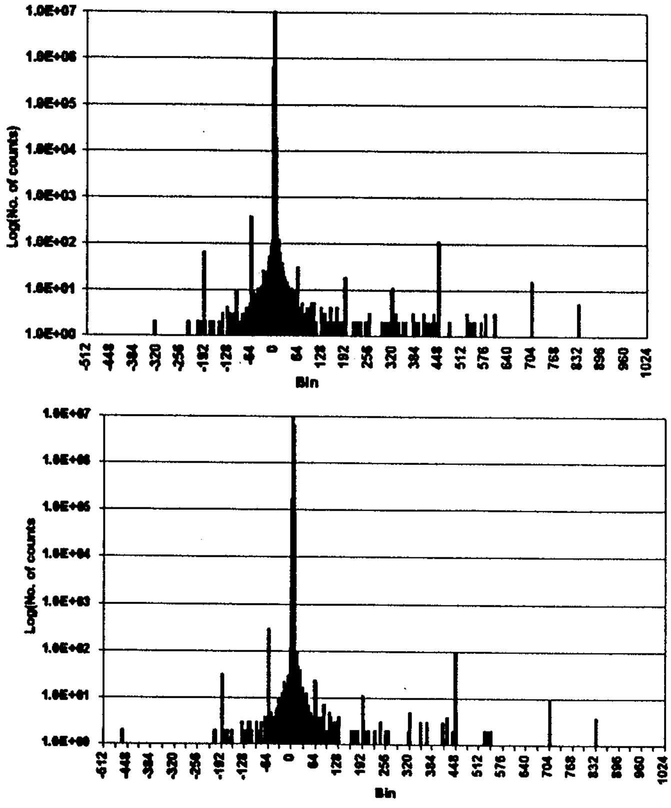

Figure 11 Ground input data for AD7884 sample B, with Ar ions at normal incidence for two separate tests, effective LET 14.10 MeV cm^2/mg, flux $5.0x10^3$ $cm^{-2}s^{-1}$ and fluence $1x10^6$ cm^{-2}.

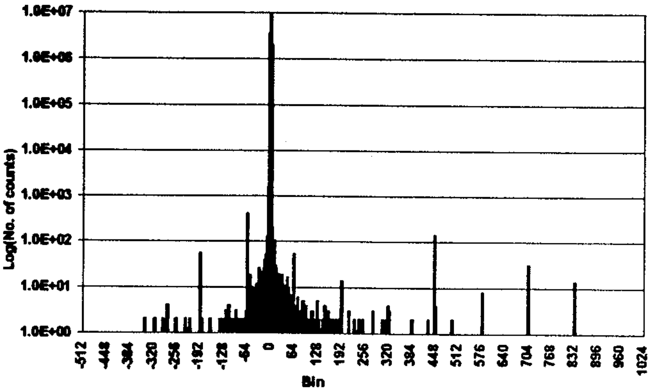

Figure 20 Ground input data for AD7884 sample B, with Kr ions at normal incidence, effective LET 34.00 MeV cm^2/mg, flux $10.0x10^3$ $cm^{-2}s^{-1}$ and fluence $1x10^6$ cm^{-2}.

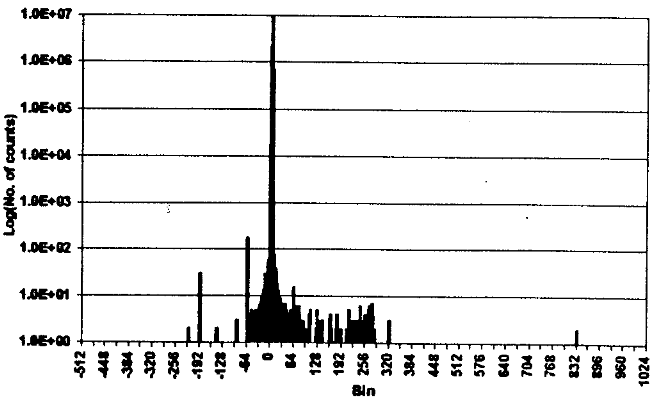

Figure 21 Ground input data for AD7884 sample B with neon ions at normal incidence. The effective LET was 5.85 MeV cm2/mg, flux $5.0x10^3 cm^{-2}s^{-1}$ and total fluence $1x10^6 cm^{-2}$.

With saw-tooth input, transient noise events were again observed over the full range of LET used (between 1.7 and 68.0 MeV cm^2/mg); however, in contrast to the ground input testing, *the phenomenon of upset events of the same magnitude being observed over several separate irradiation tests was much less pronounced.* Measurements of the transient event cross section are summarized in figure 23. The agreement with the earlier ^{252}Cf data [11] is reasonable considering that there were small differences in the threshold criteria used for counting errors. Hence the sensitive volume of the device is probably within a few μm of the surface of the AD7884 die (otherwise the ^{252}Cf data would lie below the the cyclotron data since the LET of ^{252}Cf fission fragments decreases rapidly with depth). There was no significant change in differential non-linearity during these tests.

C. The 12 bit AD7893SQ-10

Relatively few transient upset events were observed for the AD7893 under heavy ion irradiation. The upset event cross section data are given in 24. Ground input and saw-tooth tests gave similar results. The ^{252}Cf data is also shown for comparison. The cross section is lower, probably because of the fall-off in LET with depth, as mentioned above - indicating that the sensitive volume is somewhat deeper in this device than with the AD676 and AD7884 (though no details are available from the manufacturer to verify this). No significant changes in the DNL of this device were observed during the course of the tests carried out.

IV. CONCLUSIONS

Noise events were observed in all three ADC types tested. The AD7884 had the largest transient event cross section, being of the order of $2x10^{-3}$ cm^2/device. The AD7893 was the least sensitive, having a transient event cross section of the order of $3x10^{-5}$ cm^2/device. These events result from the transient deposition of charge by the heavy ions during the conversion cycle. Although most events lie close to the expected ADC value, large error events (anywhere in the ADC output range) can be seen. Clearly instrument design must take into account that large, (though rare) events can occur. Even with the extensive testing reported here, the statistics were not good enough to show error rate as a function of error size. However, since events close to (within ±15 bit) the expected value were excluded from the analysis, the cross sections essentially relate to these 'large' errors.

Like many 'new' types of CMOS high precision, high speed ADC, the 16 bit ADC676 has a digital circuit for autocalibration. Events in this device lead to what we have termed 'lingering errors' since they persist after the initial triggering event has passed. These can be regarded as an example of the single event functional Interrupt (SEFI) described by Koga [9]. The 'temporary latch-up' in the AD676 (which could only be recovered after a power off/on) may also have resulted from a type of functional interrupt. The cross section for lingering errors was somewhat larger than the transient cross section for the AD676 (of the order of $2x10^{-4}$ cm^2/device) and provision for automatic re-calibration should be provided for this (and similar) devices, particularly as the LET threshold is below 1.70 MeV cm^2/mg.

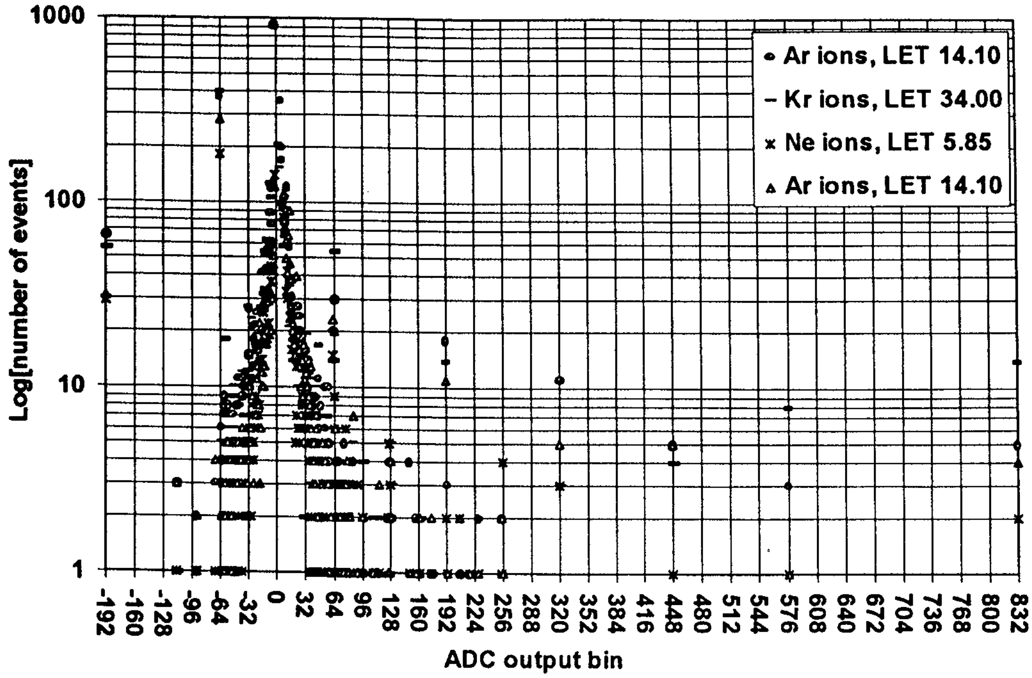

Figure 22 Transient upset events which consistently occurred in the same ADC output bin during all four ground input tests for AD7884 sample B. In addition to the events illustrated in this graph, the ADC output bin 3904 showed 2, 5, 3 and 2 events recorded with respect to the order of the legend key shown in the graph. The units for LET given in the legend are MeV cm^2/mg.

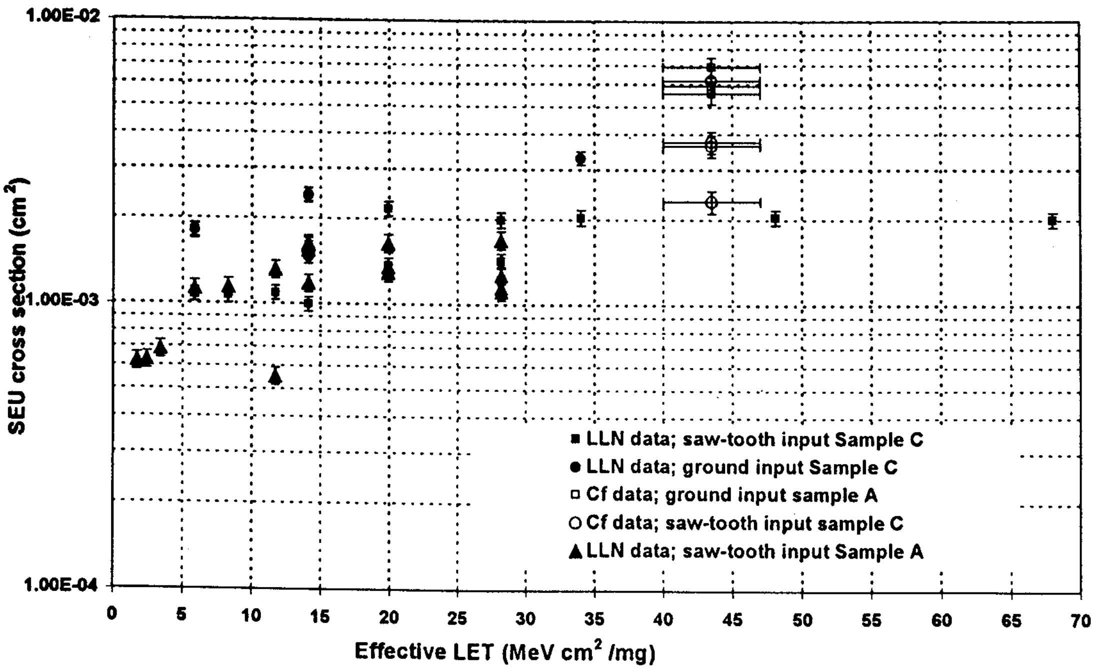

Figure 23 All transient upset event data measured for the AD7884 samples A and B.

The tests were performed with both static and dynamic inputs applied to the ADCs. On the whole the effects were similar but with the AD676 it was noticed that lingering errors of the type where the output became 'jammed' to a particular value only occured with saw-tooth tests. However this may well be because only static 0V input was used rather than a range of static voltages. With the AD7884, the static data showed a preference for the transient events to occur in particular ADC bins and this was not seen with saw-tooth tests. Again this may be due to the single 0V static input used, but it does indicate the value of saw-tooth tests in giving an overall transient response histogram in a short time. The reason why the ground input transient data for the AD7884 showed a preference for particular bins is not known. The number and magnitudes of events with equal magnitude was observed to increase as the incident heavy ion LET increased.

The earlier ^{252}Cf data [11] was demonstrated to be useful in validating the test equipment and test methods and it gave a good insight into the types of errors that can occur (both transient and lingering) and their approximate saturation cross-sections. However this work has shown that the cyclotron data gives a more accurate saturation cross-section and, most importantly, indicates that the threshold cross-section is less than 1.7 MeV cm^2/mg.

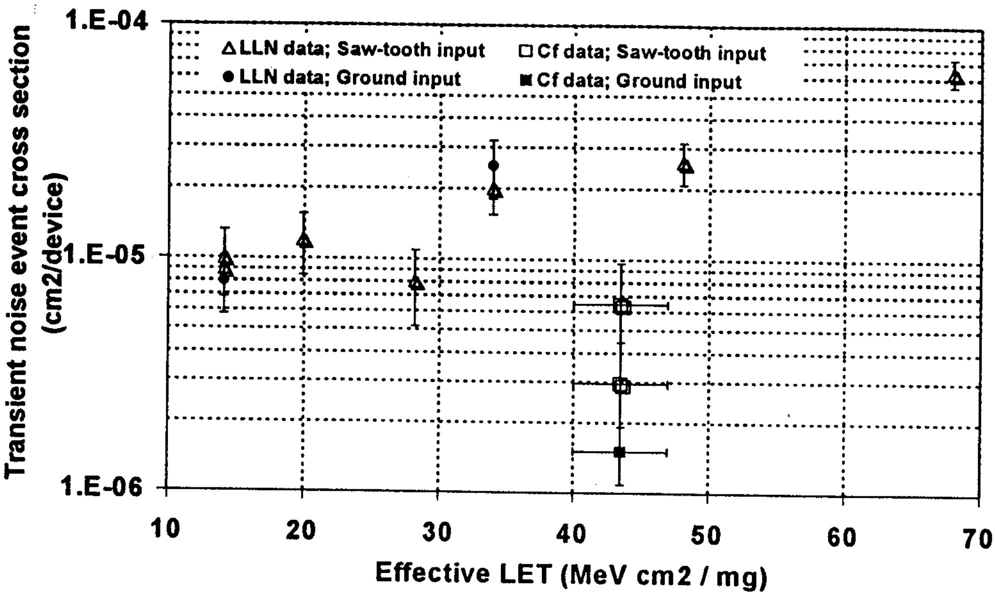

Figure 24 The transient upset event cross section data observed for the AD7893 under irradiation with heavy ions at the cyclotron.

V. ACKNOWLEDGMENTS

This work was carried out under a collaboration between ESTEC, Sira Ltd. and The Mullard Space Science Laboratory, University College London and contributed towards the principle author's Ph.D. program, which was undertaken with support from The United Kingdom's Department of Trade and Industry and the Engineering and Physical Sciences Research Council under The Postgraduate Training Partnership established between Sira Ltd. and University College London.

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