SINGLE-EVENT EFFECTS IN RESOLVER-TO-DIGITAL CONVERTERS[1]

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Abstract

Single-event effects (SEE's) in two resolver-to-digital converters (RDC's) have been studied using heavy ions and pulsed laser light. The important role of the pulsed laser in establishing single-event upset (SEU) and single-event latchup (SEL) levels prior to accelerator testing is described, as is its role in evaluating the test software and hardware and in gaining a better understanding of the origins of the SEE's. Results from pulsed-laser testing are in quantitative agreement with those from heavy-ion testing: the RDC-19220 is sensitive to both SEU's and SEL's whereas the AD2S80 is less sensitive to SEU's and immune to SEL.

I. INTRODUCTION

RDC's are integrated circuits (IC's) that convert a resolver's analog output (a measure of angle of rotation of a shaft) to a digital value of angle. They can be used to measure and control a shaft's angle, angular velocity and acceleration and, as such, have important applications in space for controlling the movement of antennae, telescopes, robotic arms, etc.

The resolver itself is an electromechanical device consisting of a rotor and two stators. Most modern resolvers are of the brushless type where the rotor excitation is transformer-coupled to the shaft rotor windings instead of being coupled via brushes and slip rings. Surrounding the shaft are two stator coils separated by 90°. As the shaft rotates, it induces in each of the stator coils sinusoidal voltages that are 90° out of phase with each other. Simultaneously, a high-frequency sinusoidal reference signal is coupled via the rotor windings into the stator windings. Therefore, each stator output consists of a carrier wave – the reference signal - modulated by a slower sinusoidal wave, i.e., $A\sin(\omega t)\sin(\theta)$ and $A\sin(\omega t)\cos(\theta)$, where ω is the angular velocity of the reference signal and θ is the shaft angle. These two outputs form the two inputs to the RDC's.

The effects observed during SEE testing are best understood after a brief description of RDC operation[1]. Though similar in function to analog-to-digital converters (ADC's), RDC's also contain feedback for control[2]. Fig. 1 shows the functional blocks comprising both RDC's tested. Functionally they are identical, although RDC's manufactured by different companies implement the functional blocks using different circuit components. For instance, the multiplication performed in the control transformer is, in the case of the AD2S80, achieved with capacitors and, in the case of the RDC-19220, with resistors.

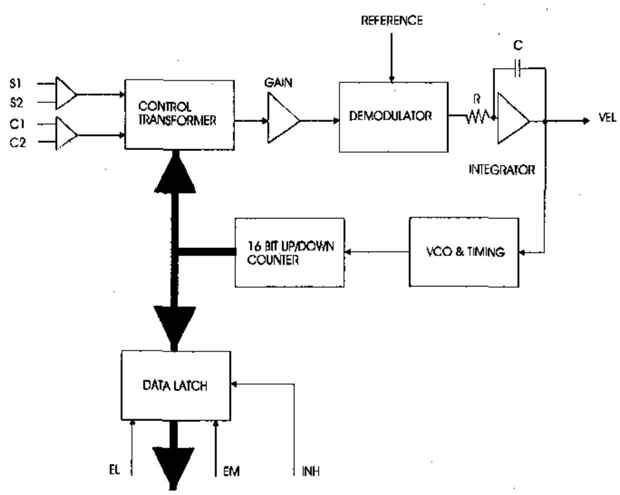

Fig. 1. Functional blocks depicting the operation of an RDC. The actual implementation varies from one manufacturer to another.

Each input signal to the RDC is first amplified before being processed by the control transformer. Then the $\sin(\theta)$ and $\cos(\theta)$ inputs are multiplied by $\cos(\phi)$ and $\sin(\phi)$, respectively, where ϕ is the digital angle in the up/down counter. Next, the control transformer takes the difference of the two multiplicands, producing an output $\sin(\omega t)\sin(\theta-\phi)$. When the shaft angle ($\theta$) is not equal to the angle in the up/down counter (ϕ), the output of the control transformer is a non-zero "error" signal. This "error" output is first amplified and then demodulated using the same reference signal $\sin(\omega t)$ applied to the resolver. The demodulated signal is integrated, and the DC voltage output is used both as a measure of the angular velocity (VEL) and as the input to a voltage-controlled oscillator (VCO). As long as its input is non-zero, the VCO sends pulses to the up/down counter to increment or decrement the stored digital angle in a direction to reduce the "error" signal. When $\theta = \phi$, the error signal is zero, and the VCO stops firing. The angle (ϕ) stored in the up/down counter also appears in the output data latch, from

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where it can be read by a computer and used to adjust the rotation of the shaft.

Evidently, RDC's contain a large number of component parts that could potentially be sensitive to SEE's, from amplifiers to latches and logic components. Therefore, we characterized the performance of RDC's in a radiation environment by exposing them to heavy ions at an accelerator. However, it is difficult (if not impossible) to interpret the heavy-ion SEE data in such a complex circuit. This is because, in an accelerator experiment, the ions can strike any location in the circuit at any time. This lack of spatial and temporal information is a significant hindrance to understanding the origins of SEE's in an RDC. Therefore, we used a pulsed laser to obtain the detailed spatial and temporal information on SEE's by injecting errors in the RDC's at known locations and times[3]. The information obtained with the pulsed laser greatly increased our understanding of the SEE response of RDC's.

II. RDC OPERATION

The radiation response of two different RDC's was investigated. One was a monolithic RDC-19220 manufactured by ILC Data Device Corporation with a programmable resolution (10-, 12-, 14-, or 16-bit output). For testing, the resolution was set for 16-bit digital output. The second RDC was an AD2S80 manufactured by Analog Devices Inc. as a mixed bipolar/digital part also with programmable resolution that, for SEE testing, was set for 12 bits. Both are commercial-off-the-shelf (COTS) parts with no measures taken to harden them to radiation damage. The output registers are organized so that a "1" in the MSB is equivalent to an angle of 180° and a "1" in the MSB-1 is equivalent to an angle of 90°, etc. For proprietary reasons, both manufacturers were unwilling to provide information about the locations on the die of the various functional blocks described in the previous section. Nevertheless, we were able to identify the locations of the output registers in both RDC's from their proximity to the output pins and from the fact that they consist of sixteen identical structures, each one a latch. We also assumed that the up/down counters contain 16 identical latches that are contiguous with the output registers. This assumption was confirmed in the case of the RDC-19220 because of the nature of the transients induced by the pulsed laser.

III. TEST EQUIPMENT AND METHOD

The RDC's were tested without actually connecting the devices to a resolver. Instead, a converter card (DSC-36020) in an IBM-compatible computer emulated the function of a resolver by providing sin(θ) and cos(θ) functions, modulated by the reference signal, for the RDC inputs. With the use of the appropriate software, the angle or angular velocity could be set, and the values continuously monitored. For reasons of simplicity, the angle was fixed and the digital output during heavy-ion irradiation was monitored. An SEU manifested itself as a temporary change in the value of the angle stored in the register, and hence read by the computer. All errors were corrected by the computer software that maintained a fixed value for the shaft input angle. Inherent noise in the system appeared as rapid random changes in the values stored in some of the least significant bits (LSB's) of the up/down counter and output register: the number of affected bits depended on the noise level. Because noise obscured the presence of SEU's in some of the LSB's, steps were taken to minimize it, although it could not be eliminated completely. To prevent noise pulses from being registered as SEU's, limits were set that bracketed the selected angle from above and below. Prior to testing, the limits were adjusted so that the variations in angle induced by the noise did not exceed the limits. Therefore, in the absence of radiation, no false SEU's were recorded. During irradiation, any angle outside the limits was recorded as an SEU.

The occurrence of SEU's was monitored in real time by graphically displaying the contents of the output register – the digital angle – on a computer monitor. The value of the output angle is represented by a displacement along the y-axis proportional to its magnitude. Each reading results in a new point shifted along the x-axis (equivalent to time). In the absence of noise and SEU's, successive readings of the output angle would generate a horizontal line on the monitor. A change in angle induced by either noise or an SEU appeared as a point displaced from the horizontal line a distance equivalent to the change in the angle. For example, an SEU that changed a "0" in the MSB to a "1" appeared on the monitor as a point displaced by the equivalent of 180° in the y direction. Angular readings were updated approximately every 10 ms. Only those changes that exceeded the noise limits (and were therefore due to SEU's) were recorded in a file for later analysis. A counter on the screen kept track of the total number of SEU's.

IV. SYSTEM VALIDATION PRIOR TO ACCELERATOR TESTING

Because the RCD is a relatively complicated part, containing many different functional blocks, the nature and origins of SET's are expected to be more complicated than for the case of simple memories, such as SRAM's. Therefore, the software and hardware were checked for proper operation by irradiating the individual RDC's with focused pulsed laser light using NRL's SEE Pulsed Laser Facility. This proved invaluable because it made possible the observation of SET amplitude and duration prior to accelerator testing, thereby aiding in the development of the software for capturing and storing the SET's.

Without information as to the locations on the die of the various functional components, it was necessary to scan the light across the die to identify SEE-sensitive areas and observe their characteristics. Surprisingly, large areas of both

RDC's yielded no observable SEU's. This could be caused either because small changes in angle affected only those bits within the noise limits, or by the absence of SEU-sensitive nodes in the area scanned. Metal coverage was not sufficient to prevent light from reaching SEE sensitive areas. However, when the area closest to the data output pins was irradiated, large changes in angle output were observed for both parts. For instance, when areas assumed to contain the MSB's of the output registers in each of the two parts were irradiated, very narrow pulses, having amplitudes equivalent to a change in angle of 180°, were clearly observed on the monitor. In the case of the RDC-19220, much longer pulses (up to 590 ms in duration) were produced when the up/down counter was irradiated. Latchup was also observed in parts of the RDC-19220. Rough measurements showed that both short and long duration SEU's had lower thresholds than latchup, indicating that it should be possible to establish the upset and latchup thresholds separately during accelerator testing. No SEL's were detected anywhere in the AD2S80, and its SEU threshold was higher than for the RDC19220. This kind of information, obtained with a pulsed laser prior to accelerator testing, proved extremely valuable for verifying that a complicated system, being used for the first time, would perform properly during heavy-ion testing, as indeed it did. Not having to make modifications to software and hardware during accelerator testing is both a financial benefit and a boon to efficiency.

V. HEAVY ION TEST RESULTS.

SEE testing using heavy ions was performed at the Lawrence Berkeley 88" Cyclotron using the low-energy-cocktail beam (4.5 MeV/nucleon). Prior to testing the AD2S80, the noise rejection levels were set at ±6° so that only larger ion-induced changes in output angle would be recorded. A wide variety of pulse heights, equivalent to different angle readings, was recorded. Fig. 2 shows the results when the AD2S80 was irradiated with Cu ions at normal incidence (LET=30 MeV.cm^2/mg). For an input angle of 100° the 12-bit output register contained 010001110001. The data show seven levels of upsets, some resulting in increased and some in decreased angles, suggesting that ions caused changes that affected, either directly or indirectly, the first seven most significant bits. (A direct SEU would be associated with an ion strike in the register itself, whereas an indirect SEU would be one that originated somewhere else in the circuit and propagated to the affected bit or bits, causing them to switch). The data show that some SEU's switched the MSB from a "0" to a "1" causing the output angle to increase to 280°. Others switched the MSB-1 bit from a "1" to a "0" resulting in a change of angle from 100° to 10°. An upset in the 7th MSB changed the angle by only 2.8125°. The fact that such a small change in angle was observed when the noise limits were set for ±6° is because the change was on top of the noise, which varied by the equivalent of just under ±6°. There is some spread in the magnitude of the largest peaks, the origins of which are unknown at this time. The spread

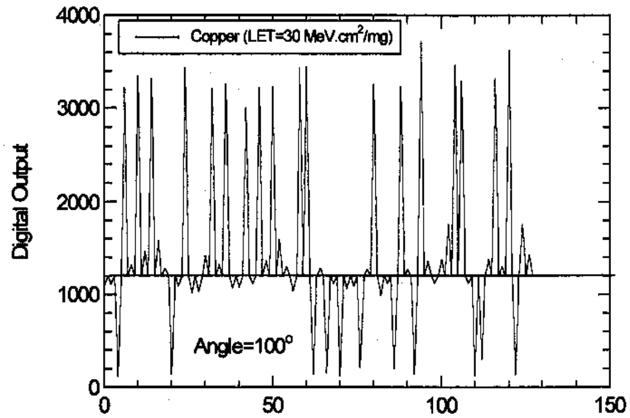

Fig. 2. SEU's recorded when the AD2S80 was irradiated with Cu ions (LET=30 MeV.cm^2/mg)

cannot be attributed to noise because the noise level, (±6°) was smaller than the spread. Additional data would have to be taken to clarify this.

Fig. 3 shows the SEU cross-section as a function of ion LET. All the SEU-induced changes in angle were included in the calculation. The data could be fit with a Weibull function with a threshold of approximately 8.75 MeV.cm^2/mg and a saturated value of 7.45x10^{-5} cm^2. No SEU's were observed for the two lowest LET's and the corresponding data points, calculated by assuming the next ion would produce an upset, were not included in the Weibull fit. No SEL's were observed up to an LET of 61.8 MeV.cm^2/mg.

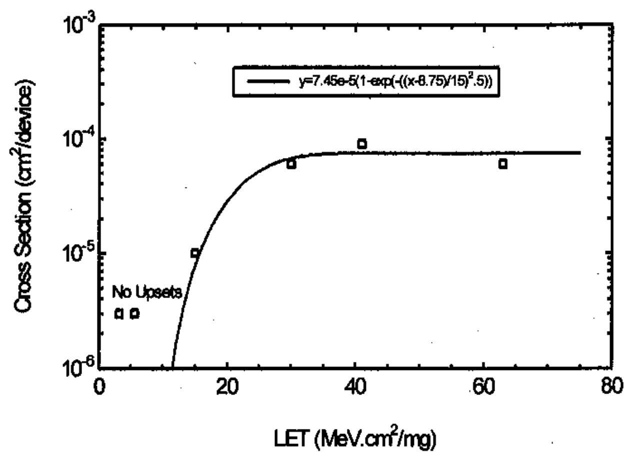

Fig. 3. SEU cross-section as a function of ion LET for the AD2S80.

Fig. 4 shows the SEU cross-section as a function of LET for two RDC-19220 parts. Two parts were tested because the first stopped functioning after suffering an SEL during exposure to ions with an LET of 5 MeV.cm^2/mg, despite the current being limited to 200 mA. For subsequent tests, the current was limited to 100 mA. SEL's appeared in the second part only for ions with LET's of 15 MeV.cm^2/mg. Therefore, the SEL threshold for this part type lies between 5 and 15 MeV.cm^2/mg. The SEL cross-section at 15 MeV.cm^2/mg was approximately 10^{-3} cm^2. No SEU's were observed during exposure to ions with LET's of 2.9 MeV.cm^2/mg, although exposure to a larger fluence might have aided in determining the SEU threshold more accurately.

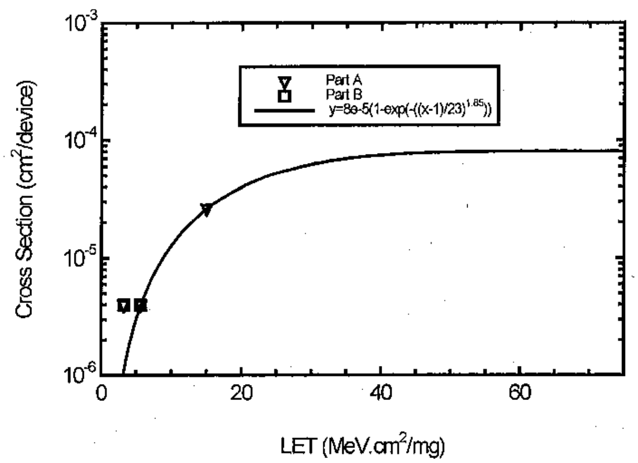

Fig. 4. SEU cross-section as a function of ion LET for the RDC-19220. Note, no upsets occurred for the lowest LET for both parts A and B. In addition, no SEU's were recorded for LET's greater than 15 MeV.cm2/mg because of the large latchup cross-section.

The large latchup cross-section at higher LET's effectively prevented the measurement of SEU cross-sections at those values. Despite having only 2 data points, a Weibull function was used to fit the data assuming a saturated cross-section close to that of the AD2S80. Again, no upsets were observed for the lowest LET and the values are not included in the Weibull fit. The fit gave an SEU threshold of approximately 1 MeV.cm^2/mg. Because of the large uncertainties, calculations of SEU rates are not advised, particularly since the large SEL cross-section and low threshold will dominate the SEE rates.

In summary, the AD2S80 is immune to SEL's and has an SEU threshold of approximately 8.75 MeV.cm2/mg and a saturated cross-section of 7.45×10^{-5} cm^2, whereas the RDC-19220 is SEL prone with a threshold between 5 and 15 MeV.cm^2/mg and has an SEU threshold of approximately 1 MeV.cm^2/mg.

VI. PULSED LASER DATA

While the heavy-ion data given above provide useful SEE information on the parts tested, such results alone provide little insight into the origin and nature of the observed SEE's. In order to identify the SEE-sensitive areas, pulsed laser light was scanned across both die. Very high pulse energies, equivalent to LET's greater than 100 MeVcm^2/mg, were used during the scans in order not to overlook SEE sensitive areas that had relatively high LET thresholds. The following results were obtained:

A. SEL in the RDC-19220

The pulsed laser was able to induce SEL in a significant fraction of the chip, primarily in the digital part that included the up/down counter and the output register. Fig. 5 is a photomicrograph of the chip and the areas outlined in black are those that exhibited latchup sensitivity. The right-hand area contains the output register and the up/down counter. The area with the lowest SEL threshold was in the output register. When the energy is converted to LET using a previously calibrated conversion factor appropriate for CMOS, a value of 8.45 MeV.cm^2/mg is obtained [4,5]. This is in quantitative agreement with the heavy-ion data that showed an SEL threshold between 5 and 15 MeV.cm^2/mg.

B. SEL in the AD2S80

The pulsed laser was unable to induce SEL in the AD2S80, even at pulse energies exceeding LET's of 100 MeV.cm^2/mg. Large open areas free of metal made it possible to probe all areas on the die for SEL. These results corroborate the absence of SEL's in the heavy-ion testing.

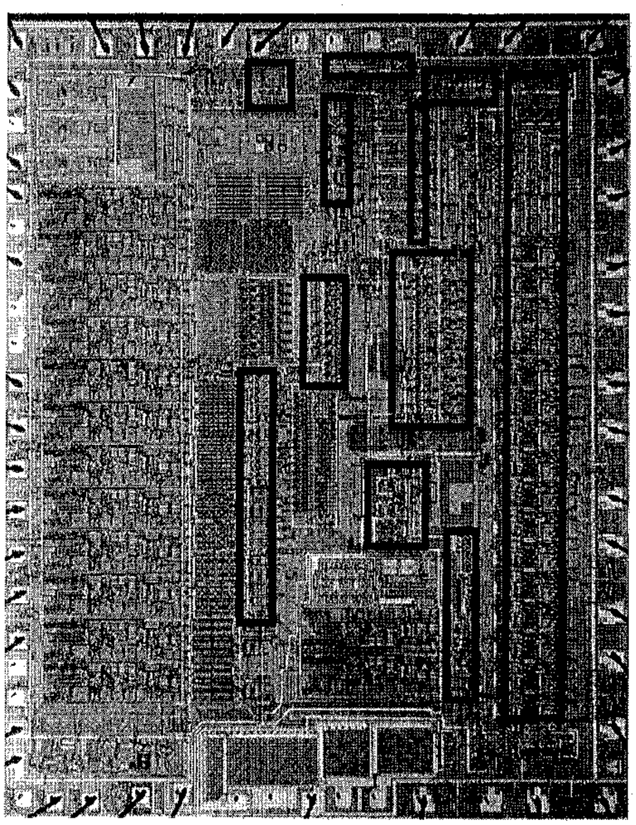

Fig. 5. Photomicrograph of the RDC-19220 showing the areas sensitive to SEL within the black rectangles.

C. SEU's in the RDC-19220

The only area on the die in which SEU's were observed is that containing the output register and the up/down counter. Fig. 6 is a photomicrograph of part of the area containing the output register and the up/down counter of the MSB. The SEU-sensitive areas are marked in the figure. With the light directed at the area marked "Short-duration SEU(0)" increases in angle of 180° that lasted ~10 ms were observed. Note that the SEU-sensitive area for a "1" in the MSB was different from that when a "0" was stored in the MSB. The short pulses in the MSB-1 had only half the amplitude but were of similar duration to the short pulse in the MSB.

The pulsed laser also makes it possible to measure the fractional time a particular node is sensitive to SEU's. This can be achieved by focusing the laser on a SEU-sensitive node and counting the number of SEU's relative to the number of laser pulses in a time interval. When the laser light, focused on the SEU sensitive area in the MSB, was pulsed at a rate of 2 Hz, the system registered 30 SEU's in 1 minute, revealing the fact that only half of the laser pulses produced SEU's.

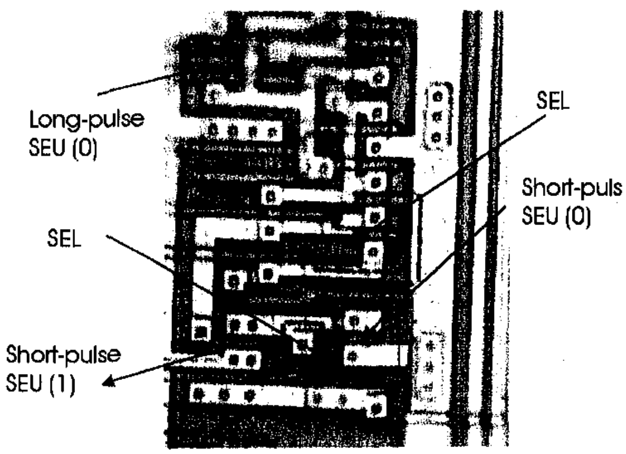

Fig. 6. Photomicrograph of the output register and up/down counter for the MSB. Also indicated are the locations of the "short-pulse SEU" and the "long-pulse SEU", for "0" and "1" stored in the latch. The area depicted here is just to the left of the bonding pin second from the bottom on the right-hand side of figure 5.

Irradiating the area designated "Long-pulse SEU(0)" in the MSB column resulted in much longer transients, characterized by a rapid (~10 ms) rise or fall followed by a much longer recovery (~590 ms. Long-duration pulses also appeared for the MSB-1, but they had amplitudes only half that for the MSB and the recovery time was only half as long (~300 ms).). Fig. 7 shows an example of the long pulse for the MSB-1. Long-pulse SEU's in bits even further from the MSB produced smaller amplitudes and shorter transients.

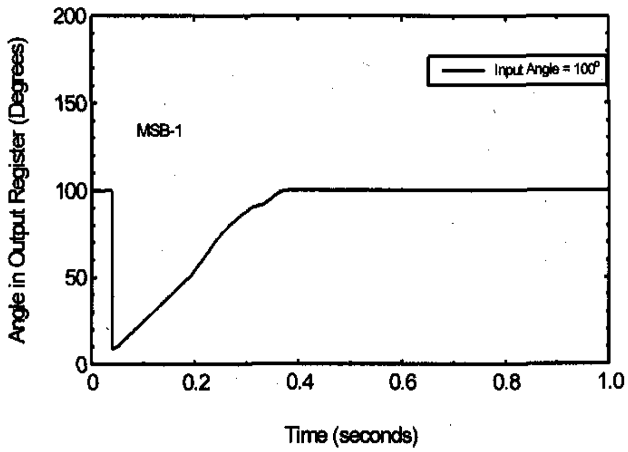

Fig. 7. An example of the "long-pulse SEU" generated in the MSB-1 register. The recovery time is approximately 300 ms.

The fractional amount of time the nodes responsible for "long-pulse SEU's" was also measured using the method previously described. For these nodes, SEU's were registered for every laser pulse, implying there were sensitive 100% of the time.

The figure shows that the areas most sensitive to SEU's (short and long pulses) were well separated, as was the area sensitive to SEL. Hence, using the laser, it was possible to measure the thresholds for the three different phenomena. Table I shows the SEE thresholds measured for the short-pulse SEU, the long-pulse SEU, and SEL. The same conversion method described previously was used.

Table I.
LET threshold measured for three different SEE effects in the RDC-19220.

SEE EFFECT	LET THRESHOLD MeV.cm^2/mg
Short-Pulse SEU	3.9
Long-Pulse SEU	6.3
SEL	8.45

D. SEU's in the AD2S80

As in the case of the RDC-19220, scanning the entire die with high-energy pulses of laser light only produced SEU's in those areas assumed, because of their location and repeated structure, to contain the output register and up/down counter. Fig. 8 shows the locations of six distinct SEU-sensitive areas in one of the 16 columnar structures – the one associated with the MSB. All the areas designated as SEU-sensitive, except "D", resulted in exactly the same transient change of angle, i.e., with the shaft angle set at 100°, an SEU in the MSB caused the bit to change from "0" to "1" and the

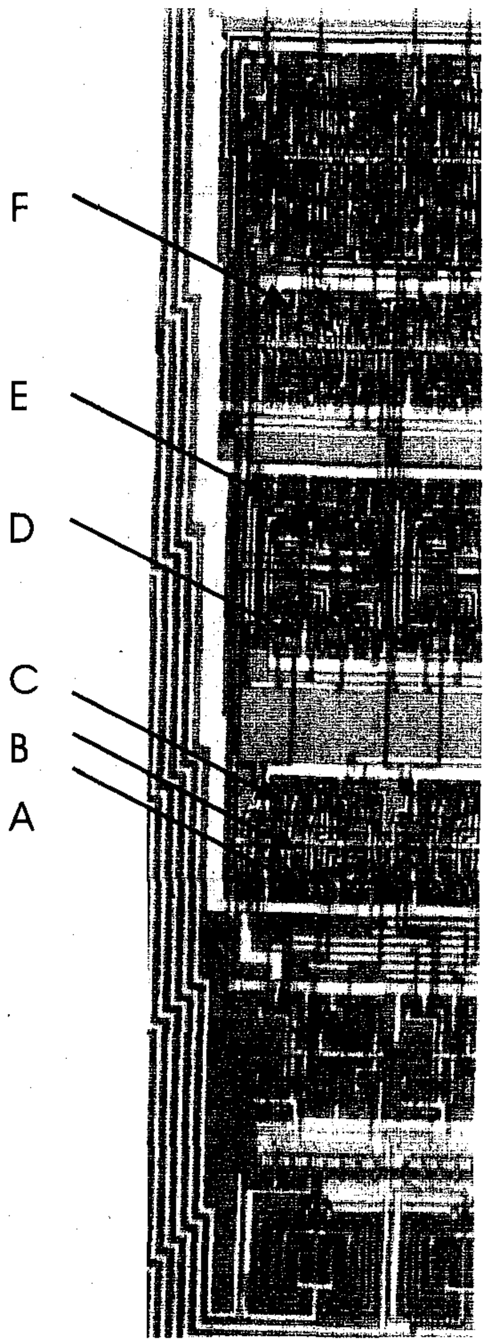

Fig. 8. Photomicrograph of the area on the AD2S80 containing the up/down counter and the output register of the MSB. There are six nodes, marked A through F, that are SEU sensitive when a "0" is stored in the MSB.

angle to change from 100° to 280°. The duration of the transient was less than 10 ms in all cases. As expected, when the shaft was set at 200°, i.e., the MSB = 1, different areas in the MSB column were SEU sensitive, and SEU's caused the digital output angle to change from 200° to 20°. However, when the SEU-sensitive area marked "D" was irradiated, the digital output angle varied for each pulse, suggesting that upsets in the area somehow affected all of the bits in the output register. Lacking the necessary information from the manufacturers, we are unable to explain this effect.

The threshold energies at each of the SEU-sensitive locations were measured. Table II shows the equivalent LET values after conversion for SEU's at the six locations. The table shows that the most sensitive areas are those labeled "B" and "C", with their LET thresholds being about 1/4 of that required to produce upsets at location "D" where the digital output angle varied for each pulse. This suggests that areas "A", "D" and "E" do not contribute to the SEU cross-section in the vicinity of the threshold. These results suggest that their contributions become significant at LET's greater than 25 MeV.cm^2/mg.

Table 2.
SEU thresholds at six different locations in the MSB.

LOCATION	THRESHOLD (MeV.cm^2/mg)
A	33
B	7.4
C	6.2
D	25
E	27
F	12

The time during which some of these nodes were sensitive to SEU's was measured using the same technique as for the RDC-19220. When the light was focused on node "A" and the laser pulsed at 2 Hz, there were 80 SEU's in 2 minutes, suggesting that only 2 out of 3 pulses produced SEU's. The same method revealed that node "D" upset all the time.

VII. DISCUSSION

A. SEU's in the analog parts of both RDC's

A common feature of both circuits is that SEU's were observed in only a relatively small area of the die – the up/down counter and the output register, both of which are digital. SEU's were not observed in the analog parts of the circuit. By carefully analyzing the functions of each part of the ADC's, it is not too difficult to understand why large SEU's are not recorded by the system when the analog parts are irradiated with laser light, or heavy ions.

The parts of the circuit that include the input amplifiers, the control transformer, the amplifier between the control transformer and the demodulator, and the demodulator itself should be largely immune to SEU's because the input signals are modulated and then demodulated prior to being integrated. This form of signal processing is implemented to minimize noise (including SEU's) in the circuit. The rest of the analog part of the circuit consists of an integrator and VCO & timing circuits. It is possible that SEU's in the integrator itself may cause the VCO to fire, but it is unlikely that more than a few of the least significant bits would be affected. SEU's in the VCO may cause it to fire a few times, again hardly sufficient to cause more than a few of the least significant bits to change. Consequently, those SEU's would be hidden in the noise and would not be recorded. Only SEU's in the digital parts - the up/down counter and the output register - are of sufficient magnitude to be detected by the system.

B. SEE's in the RDC-19220

Short-pulse SEU's appeared when bits stored in the output latch were corrupted. The pulses were of short duration (~10 ms) because the transfer of the uncorrupted digital data in the up/down counter rapidly rewrote the corrupted bit on the next cycle. The system was found to be sensitive to short-pulse SEU's only 50% of the time. This is because the 16 bits in the output register are read 1 byte (8 bits) at a time - first the most significant byte and then the least significant byte. If a bit in the most significant byte is corrupted while the other byte is being read, it will be restored before it can be read, and so no SEU will be registered.

Long-pulse SEU's appeared when the up/down counter was irradiated with laser light. The long recovery time is associated with the time it takes the up/down counter to return to its original value. For instance, if the MSB is corrupted, the VCO has to fire 2^{15} times before the angle in the up/down counter equals the shaft angle. If the MSB-1 is corrupted, the VCO only has to fire 2^{14} times, with the result that the system recovers in half the time and the change in angle was only half that of the MSB. During laser irradiation, the long-pulse SEU's occurred for every laser pulse. This is due to the fact that transferring the data from the output register to the computer occurs many times during the time it takes the up/down counter to return to its original value.

C. SEE's in the AD2S80

All the SEU's observed during laser testing of this part were of short duration (≈10ms), regardless of whether they had their origins in the output register or the up/down counter. A possible explanation is that the part was programmed for 12-bit resolution, so that, all else being equal, the pulse would take 1/16th the time to recover compared to the RDC-19220. Their amplitudes were as expected, i.e., an SEU that affected the MSB produced a change of 180°, etc. It appears that the timing of the data read is different from that of the RDC-19220, because nodes in the output register are sensitive 2/3 and not half of the time. Apparently, the timing scheme is different and more detailed information from the manufacturer is required to clarify this point.

Another aspect that was not understood is the function of node "D" where SEU's of different amplitudes occurred for every pulse. It is most likely associated with the up/down counter or with the transfer logic because it is sensitive to SEU's 100% of the time. Again, to clarify its function requires information from the manufacturer which, was not forthcoming.

VIII. CONCLUSION

We have used both heavy-ions at an accelerator and pulsed laser light to investigate the SEE responses of two different COTS RDC's. In our testing, we found that the RDC-19220 is far more sensitive to SEE's than the AD2S80, i.e., the RDC-19220 has a relatively low SEU threshold of 1 MeV.cm^2/mg, and is also prone to SEL with a threshold between 5 and 15 MeV.cm^2/mg, whereas the AD2S80 has an SEU threshold of approximately 8.75 MeV.cm^2/mg and is immune to SEL. Table III, which summarizes the results of heavy-ion and pulsed laser testing, illustrates the good quantitative agreement between the two techniques.

Table 3.
Comparison of SEE levels measured with heavy ions and pulsed laser light.

	RDC-19220 (MeV.cm^2/mg)		AD2S80 (MeV.cm^2/mg)	
	ION	LASER	ION	LASER
SEU	<5.5	3.9	8.8	6.2
SEL	5.5<x<14.2	8.4	None	None

Pulsed laser testing also revealed that large areas of both die (the analog parts) exhibited no detectable SEU's. This is not surprising because, as previously demonstrated with ADC's[2], SEU's in the analog part of an ADC tend to give rise to a small spread in the noise, and in our system they were effectively blocked by the levels set for noise rejection. Therefore, the only SEU's recorded with our system during both heavy-ion and pulsed-laser testing originated in the digital parts - the up/down counter and the output register.

The pulsed laser made it possible to measure not only the SEE thresholds, but also the percentage of time the different nodes were sensitive to SEU's. From the pulse duration in the case of the RDC-19220, and the percentage of time a node was sensitive to SEU's in the case of the AD2S80, it was possible to confirm which part of the die was the output register and which was the up/down counter. This type of information gives important insight into the different operations of the two devices and how they respond to SEU's.

Without the additional information obtained with the pulsed laser, both before and after heavy-ion testing, our knowledge of SEU's in RDC's would have been quite limited. With the pulsed laser we were able to obtain both spatial and temporal information on SEU's that has greatly enhanced our understanding of their origins and characteristics.

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