SEE and TID Qualification of the ELMB128 Series Production

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Abstract: Twelve ELMB128 boards from the series production were exposed to 60 MeV protons to a total fluence of $1.2{*}10^{12}$ protons/cm^2. Each board received concurrently a TID dose of 140 Gy. No destructive or permanent SEE error occurred but one of boards failed during the reprogramming of the flash memory. The number of functional soft SEEs amounted to 3. The different components of the ELMB, ATmega128 processor, CAN controller SAE81C91 and the ADC CS5523 were subject to a systematic study of their SEE cross-section. Measurements were also made on the Agilent Technologies optocouplers HCPL-0731.

1.0 Introduction

The proton irradiation of the ELMBs [1] was performed on 11 November 2003 at the CYClotron of LOuvain-la-NEuve (CYCLONE) of the Université Catholique de Louvain, in Belgium [2] with 60 MeV protons. This test follows two earlier tests made at CYCLONE 2001 [3], 2003 [4]. In addition to Single Event Effects (SEE) and Total Ionising Dose (TID) also measurements on optocouplers HCPL-0731 were made this time. The test involved twelve ELMB128 boards assembled with components from the series production. The flux varied during irradiation as shown in Figure 1. The first three boards received a flux of $1{*}10^8$ protons$*$cm$^{-2}*$s^{-1}, except one of them (Ser.No. A971). This board received by mistake a 5 times higher flux for a short period time. It was later found that this board has a TID problem described in chapter 5.1. The nine remaining boards received a flux of $2{*}10^8$ protons$*$cm$^{-2}*$s^{-1} during the irradiation period to give each a total fluence of $1{*}10^{11}$ protons/cm^2. This fluence corresponds to a TID of 140 Gy (Si).

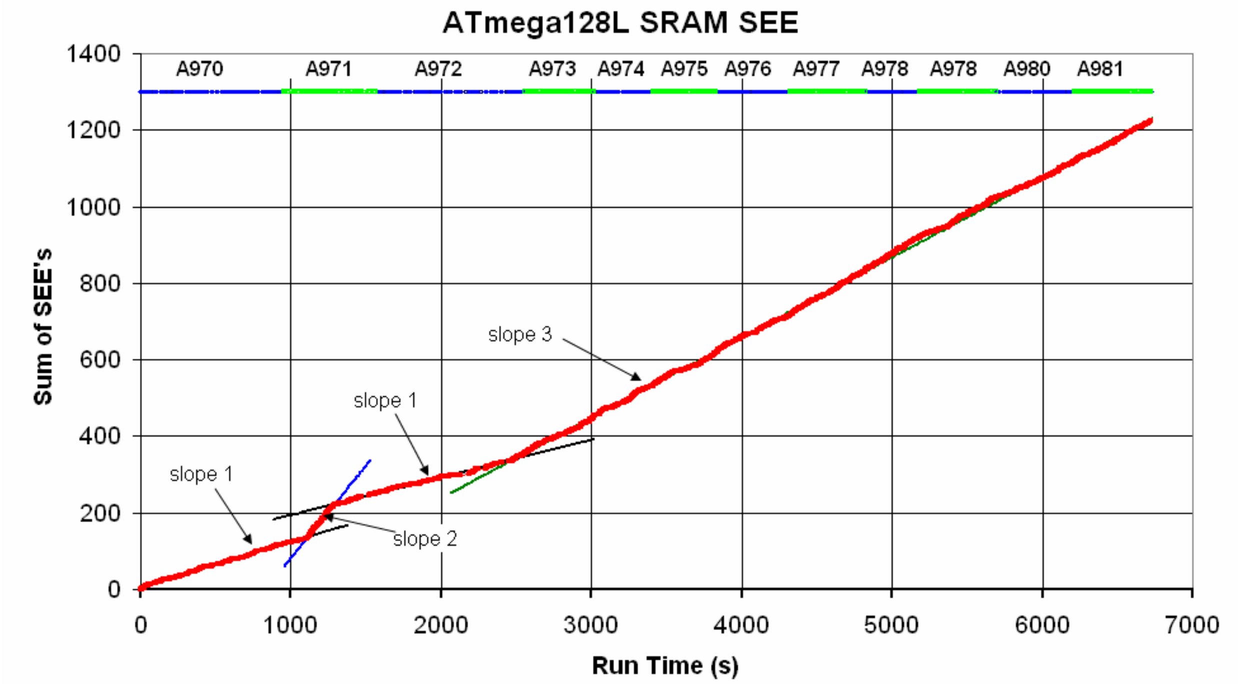

Figure 1 The measured SEE events recorded in the SRAM of the ATmega128 processor as a function of the run time. The three slopes corresponds to a flux of 1, 2 respectively $5{*}10^8$ protons$*$cm$^{-2}*$s^{-1}

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2.0 Experimental setup and test method

The twelve ELMB128s were tested successively using the same setup as in the earlier tests in 2001 and 2003. The ELMB128 boards under test were programmed with a special version of the embedded software 4.2 [5] which contained the ADC readout of 4 channels and special SEE tests of SRAM, EEPROM, flash memory, registers in the ADC circuit CS5523, CAN controller SAE81C91 and ATmega128 microcontroller. The program was executed in a test loop every 5 seconds. In addition all of the 64 ADC channels were readout every 30 sec. The input voltage to the ELMB consisted of 16 DC voltages applied to each of the four input connectors in parallel.

3.0 Results and Analysis of the functional SEE test

There were three functional SEEs for $1.2 * 10^{12}$ protons/cm^2. One concerned the ADC, while the two others the program in the ATmega128 processor.

3.1 ELMB128 with Ser.No. A973 SEE of the ADC

As shown in the Figure 2 the readout of the ADC is in overflow conditions (= 1.0E6 µV) from run-time = 400s. All of the ADC channels behaved similarly. The condition was not detected on-line. But a manual or automatic re-initialising of the ADC (soft-reset) should have cleared this condition.

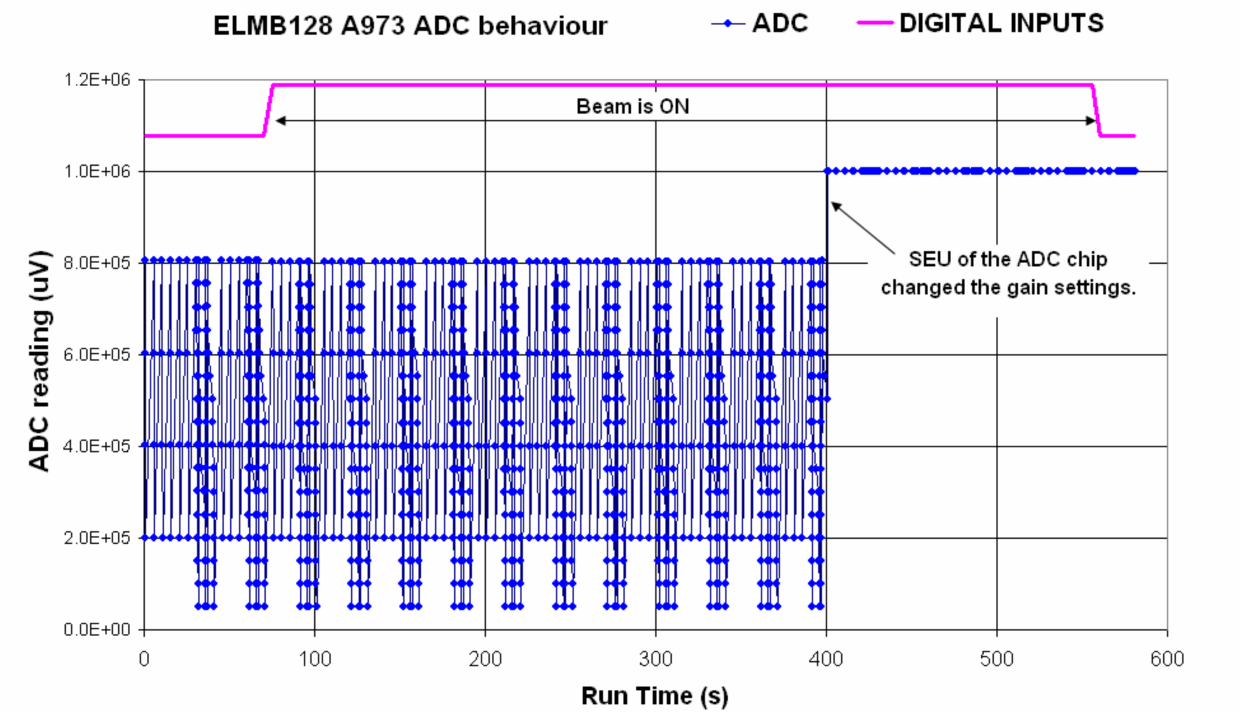

Figure 2 The normal readout of all the 64 ADC channels is shown until the time 400s. At this time one SEE in the ADC chip changed the gain settings. The digital inputs indicates the time during which the beam was on.

3.2 ELMB128 with Ser.No. A974 ATmega128L readout routine error

During the readout check of the EEPROM for SEE's the control program reported 1809 errors. The byte read from the EEPROM was always equal to FF. In the next test done 5 seconds later no further error of the readout of the EEPROM were reported. Therefore it is concluded that one SEE occurred concerning ATmega128L readout routine checking the EEPROM. The error was automatically corrected by embedded software.

3.3 ELMB128 with Ser.No. A978 ATmega128L stops to send data

The ELMB stopped to send data after 312s, see Figure 3. The CAN controller was set to auto-answer to a particular request (a so called Remote Frame Request or RTR), see Figure 4. This still worked, but a toggle bit in this reply was not updated. This means that the program in the microcontroller was not running properly. Software reset messages were sent manually with no effect. Therefore a power cycling was done manually at the time 460s and normal operation resumed.

ELMB128 Ser.No. A978 ADC Readout behaviour

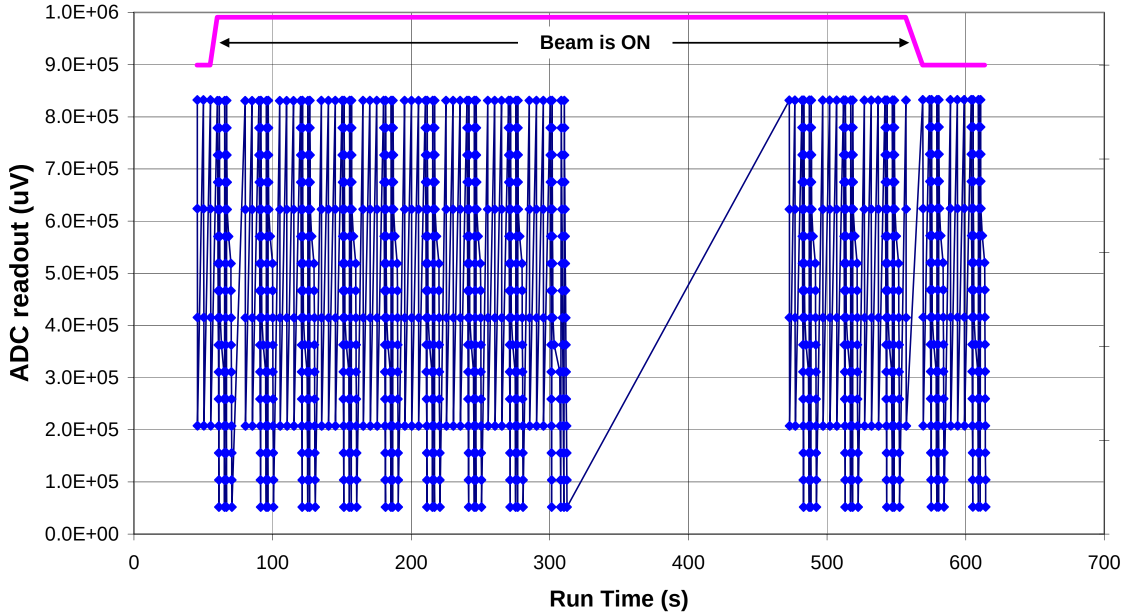

Figure 3 The normal ADC readout of 64 channels ELMB Ser.No. A978 stopped at 312s and resumed at 470s.

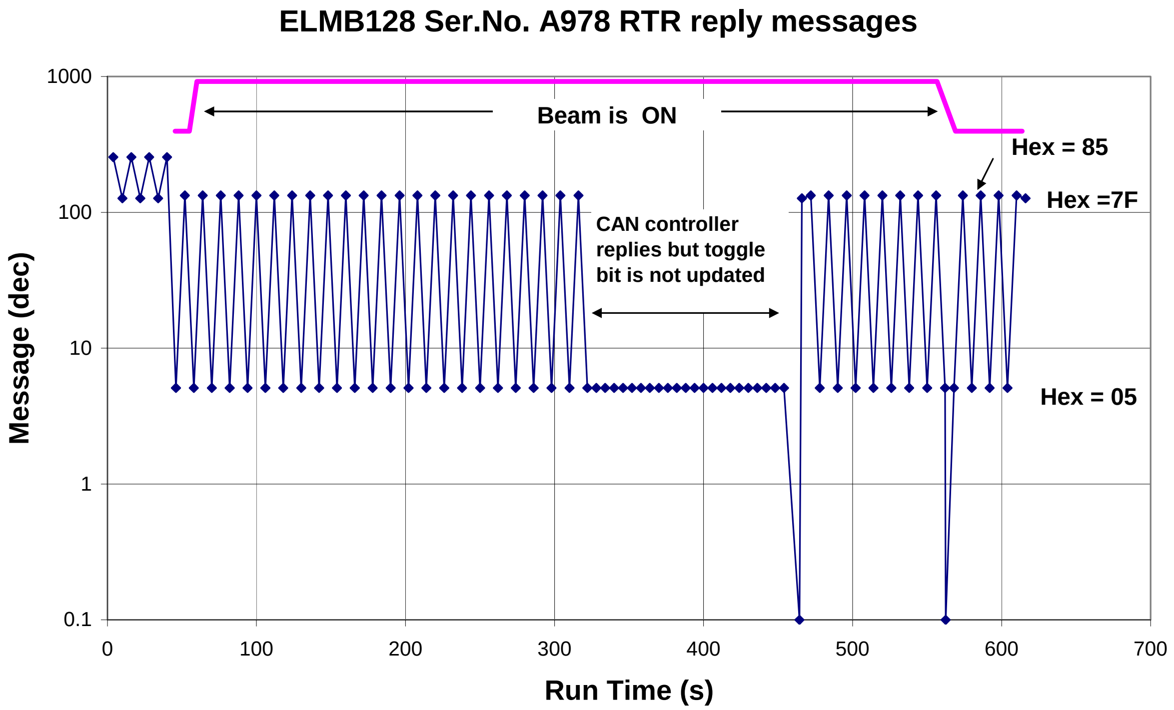

Figure 4 RTR messages showing the CAN controller replies but the toggle bit is not updated

3.4 ELMB128 with Ser.No. A978 Error frames.

Two error frames were sent by the CAN controller. This is either due to a SEE in the CAN controller or noise injected in the long CAN cable detected and automatically corrected by the CAN controller.

3.5 Summary of the results

The integrated fluence of $1.2*10^{12}$ protons/cm^2 caused neither a hard SEE nor a destructive SEE. The results of the functional SEE test are summarized in Table 1.

Table 1: Number of soft SEEs for each means of recovery

Recovery by	**Number of SEEs detected for $1.2*10^{12}$ protons/cm^2**	**Average fluence for 1 error**
Power cycling	1	$1.2*10^{12}$ protons/cm^2
Software reset	1[1)]	$1.2*10^{12}$ protons/cm^2
Automatic recovery	3	$4.0*10^{11}$ protons/cm^2
All types of recovery	**6**	**$2.0*10^{11}$ protons/cm^2**

1) ADC software reset was to be done

4.0 Results of the systematic study of SEUs in memories and registers

The results of the systematic search for SEUs in memories and registers by the dedicated ELMB software are given below and compared to earlier tests. The memories and registers of the master processor ATmega128 as well as the static registers of the CAN controller SAE81C91 and the ADC CS5523 were tested.

4.1 Processor SRAM test

The test covered 2 kBytes of the processor's embedded SRAM. Figure 5 shows the total number of SEEs detected versus the fluence for the current as well as the two earlier irradiation tests. Note the difference in slope between the most recent tests and the oldest test. This is due to a change in technology of the processor from 0.5 µm to 0.35 µm. The slopes for the old and new technologies are $3.6*10^{-12}$ respectively $5.4*10^{-13}$ and $4.9*10^{-13}$ per byte and proton/cm^2.

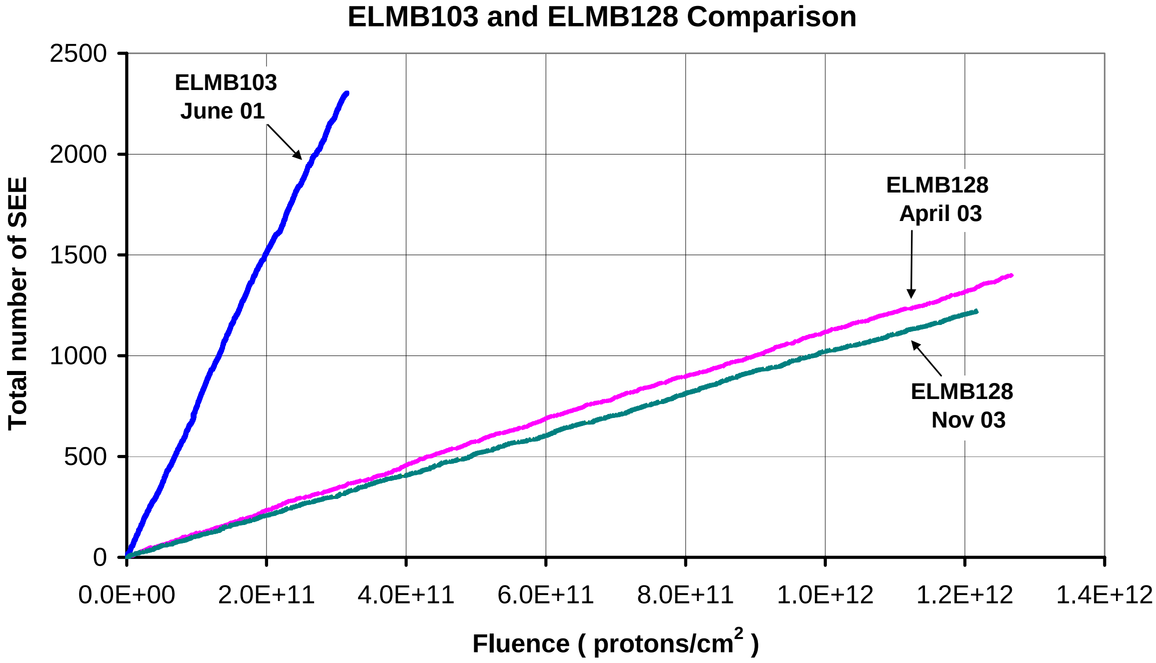

Figure 5 Total numbers of SEEs for three different processor versus fluence

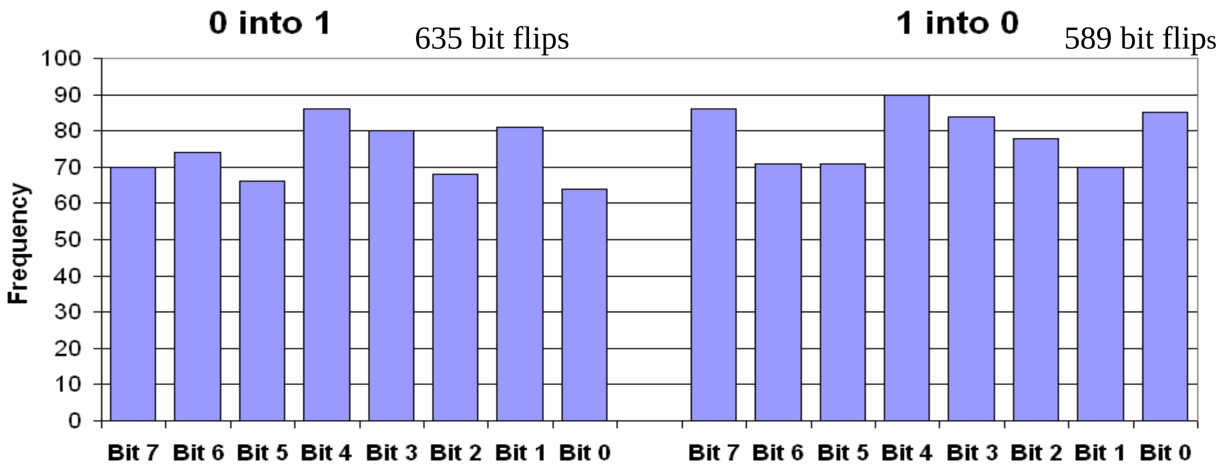

Figure 6 Number of changes from 0 to 1 and 1 to 0 in the 8 bits of the SRAM bytes The number of SEEs was 1224 single bit flips evenly distributed over bits and polarity.

The test involved addresses 0x600 to 0xDFF (1536 to 3583 in decimal). Figure 7 indicates for each SEE in SRAM the address where it was located during the run-time. Figure 8 shows the even distribution of the SEEs over the different addresses.

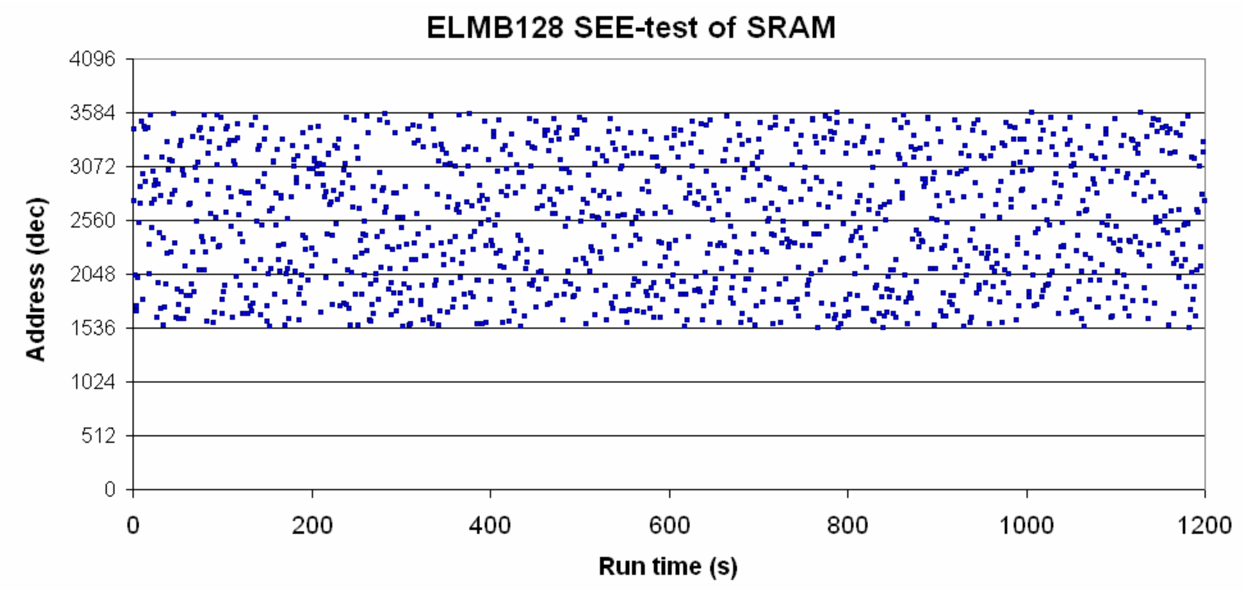

Figure 7 Addresses of the SRAM where the SEEs were located versus run-time

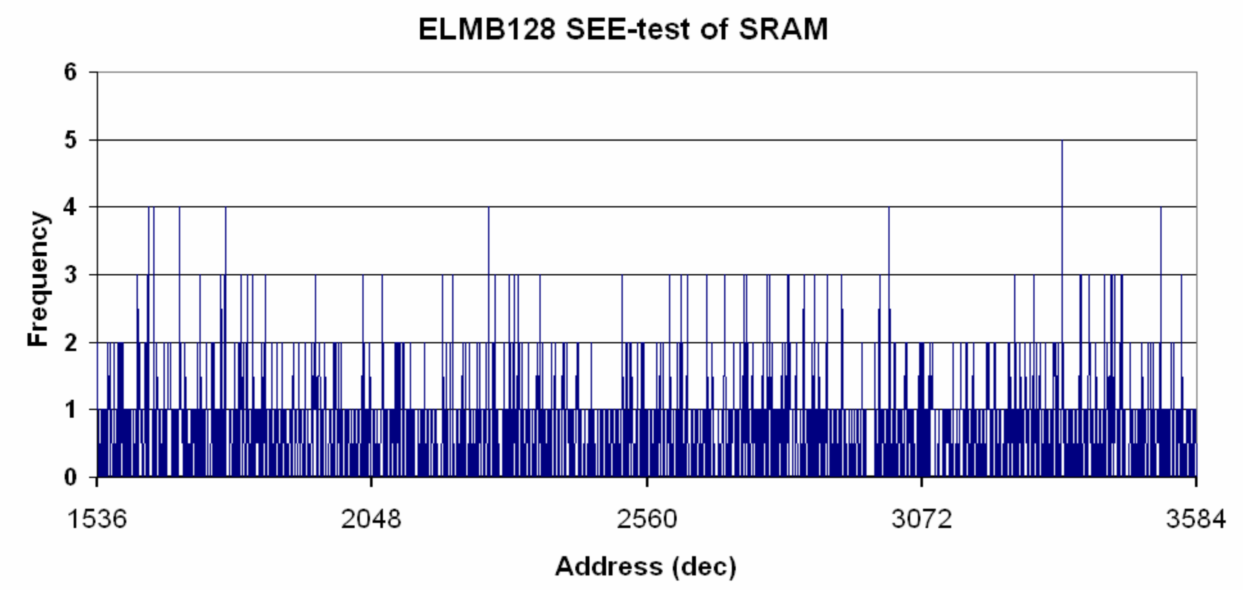

Figure 8 Number of SEEs detected in all the ELMBs per address in the SRAM

4.2 EEPROM test

The test involved 2048 bytes of the embedded EEPROM. No SEE was found. If one SEE had occurred, the cross-section would have been $4.1*10^{-16}$ SEEs per byte and proton/cm^2.

4.3 Flash memory test

57341 bytes of the embedded flash memory were tested. Its content was unchanged after the test for all ELMBs. One error would have corresponded to a cross-section of $1.4*10^{-17}$ SEEs per byte and proton/cm^2.

4.4 CAN-controller register test

The test involved 32 bytes of the registers of CAN controller SAE81C91. The total number of SEEs amounted to 59, which corresponds to a cross-section of $1.5*10^{-12}$ SEEs per byte and proton/cm^2.

4.5 ADC register test

The test involved 33 bytes of ADC registers. The total number of SEEs amounted to 5, which corresponds to a cross-section of $1.3*10^{-13}$ SEEs per byte and proton/cm2.

4.6 Microcontroller ATmega128 register test

The test involved 10 bytes of microcontroller registers. The total number of SEEs amounted to 1, which corresponds to a cross-section of $0.8*10^{-13}$ SEEs per byte and proton/cm2.

4.7 Summary of the results

The results of the study of SEUs in memories and registers are summarized in Table 2.

Table 2: Results of the systematic SEE study

Fluence: $1.2*10^{12}$ protons/cm^2

	Number of bits tested	Number of SEEs	Cross-section cm^2/bit
SRAM	16384	1224	$6.2*10^{-14}$
EEPROM	16384	<1	$<5.1*10^{-17}$
FLASH	458728	<1	$<1.8*10^{-18}$
CAN registers	256	59	$1.9*10^{-13}$
ADC registers	264	5	$1.6*10^{-14}$
ATmega128 registers	80	1	$1.0*10^{-14}$

A comparison between the three tests made at the CRC is shown in Table3 below. Concerning the SRAM the technology change reported by the manufacturer from 0.5 µm to 0.35 µm improved the SEE tolerance with a factor 7. Also the registers of the ADC show a considerable improvement by a factor 20 compared to the first test in 2001. The sensitivity to SEE of the registers of the CAN controller was the same within the statistical errors for all tests. It is worth to mention that no error was seen in the EEPROM and FLASH memories in three tests, which amounted to a total of $3*10^{12}$ protons/cm^2.

Table 3 Comparison of the results of three ELMB SEE tests

DUT	**ELMB128** Nov 2003 cm^2/bit	**ELMB128** April 2003 cm^2/bit	**ELMB** June 2001 cm^2/bit	Comments
SRAM	$6.2*10^{-14}$	$5.7*10^{-14}$	$43*10^{-14}$	Technology change ATMEGA128L
EEPROM	$<5*10^{-17}$	$<3*10^{-17}$	$<10*10^{-17}$	Test limited
FLASH	$<2*10^{-18}$	$<0.7*10^{-18}$	$<3*10^{-18}$	Test limited
CAN registers	$1.9*10^{-13}$	$0.72*10^{-13}$	$2.2*10^{-13}$	
ADC registers	$1.6*10^{-14}$	$0.87*10^{-14}$	$25*10^{-14}$	Technology change ADC CS5523 **?**
ATmega128 registers	$1.0*10^{-14}$	$<1.0*10^{-14}$	Not tested	

Table 4 Comparison of the results of three ELMB SEE tests

CRC test date	**ELMB128** Nov 2003	**ELMB128** April 2003	**ELMB** June 2001
Average fluence for 1 functional error	$20*10^{10}$ protons/cm^2	$9*10^{10}$ protons/cm^2	$1.1*10^{10}$ protons/cm^2

The Table 4 shows the average error rate versus fluence. The consistent improvements between runs are due to both hardware and the embedded software.

5.0 TID effects

The Total Ionizing Dose received by each of the 12 ELMB boards was 140 Gy (Si).

5.1 Reprogramming function of flash memory and EEPROM

The reprogramming function of the flash memory of all ELMB boards was tested immediately after each proton irradiation. The tests of the first two boards were done in steps at 35 Gy, 70 Gy, and 105 Gy to find out if the reprogramming function stopped to work. The tests on the other ten boards were done after the completed run of 140 Gy. Eleven of the boards could be programmed after 140 Gy. One of the boards (the second in the test - A971) failed during the programming of the flash memory after having received 140 Gy. It is likely that this failure is due to the fact that this board received 5 times the intended flux during a period of time due to a mistake in the operation of the proton beam!

After the boards were returned to CERN on 9 March 2004 they were retested in the ELMB test box. All boards passed except the A971. This board failed during the programming of the flash memory. During this operation the digital current suddenly increased from 12 mA to 45 mA. This A971 failed to work after this.

5.2 Power supply currents

The analog, digital and CAN power supply currents were measured with the test box at CERN before the test and at CERN after the test. The differences between the two values are displayed in the charts below. They are all very small and within the specification.

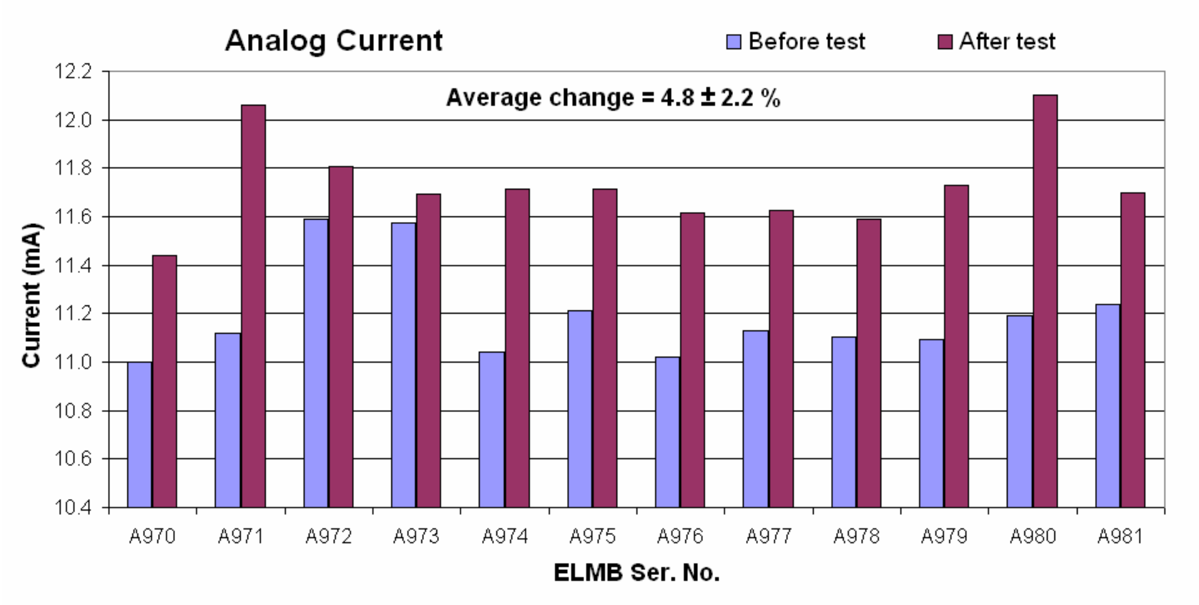

Figure 11: Change in the analog current after the irradiation

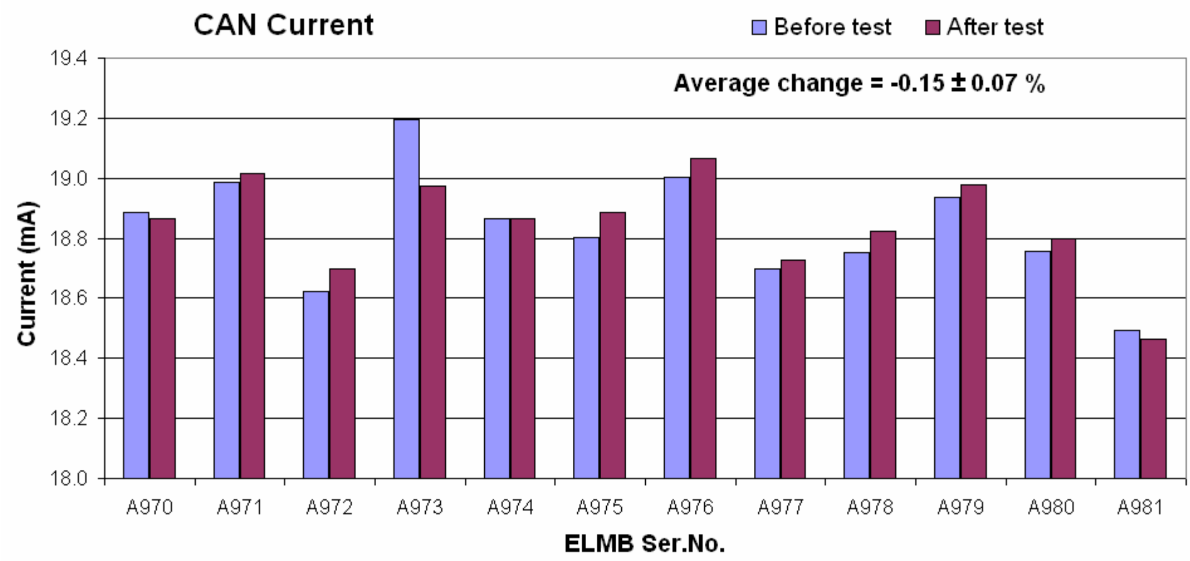

Figure 12: Change in the CAN current between the beginning and the end of the test

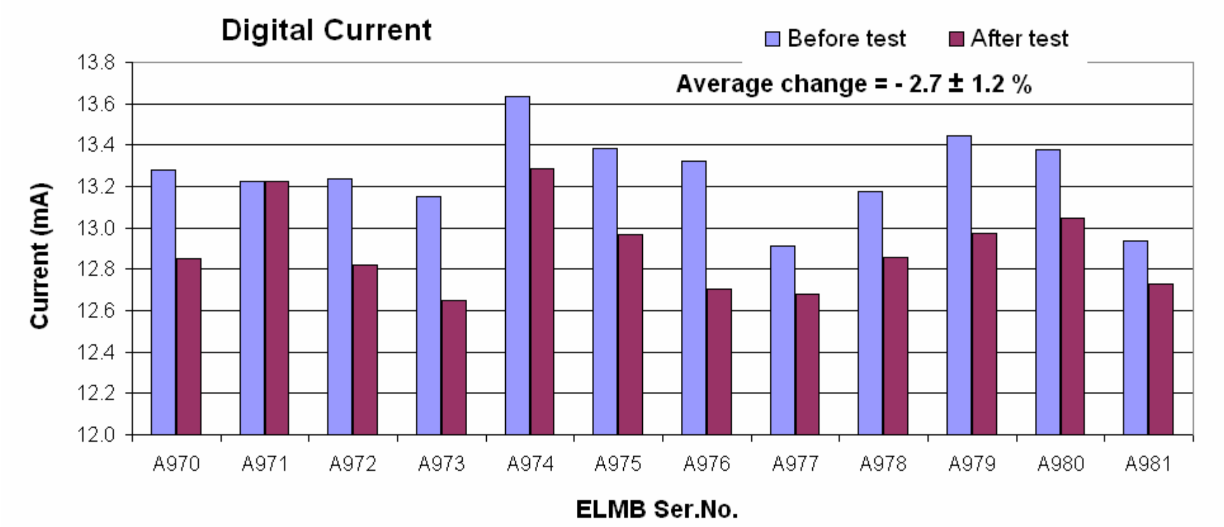

Figure 13: Change in the digital current between the beginning and the end of the test

5.3 DC voltages

The ADC voltage reference AD680JR was very stable (10^{-3}).
The voltages of the analog, CAN and digital regulators changed slightly but stayed within the specification of ± 3%.

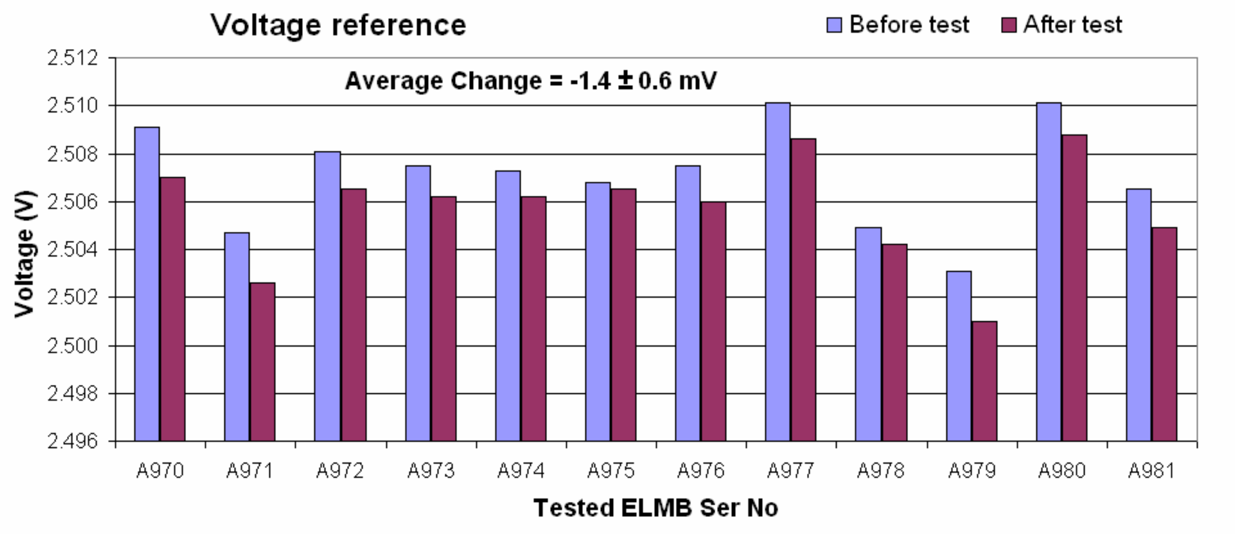

Figure 14 Change in the ADC voltage reference is -0.06%

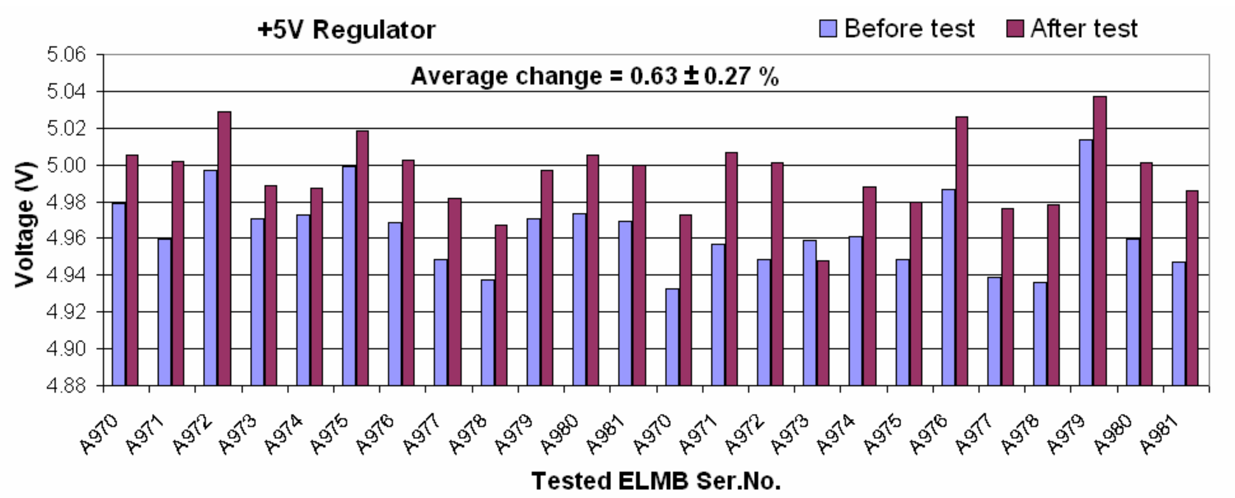

Figure 15 Changes in the 5V regulator

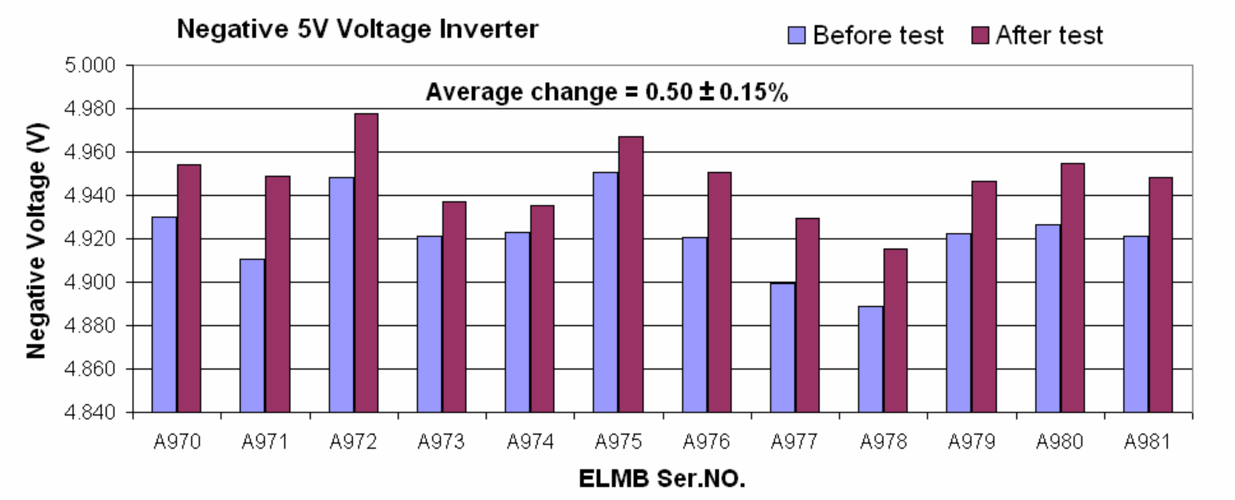

Figure 16 Changes in the -5V voltage inverter

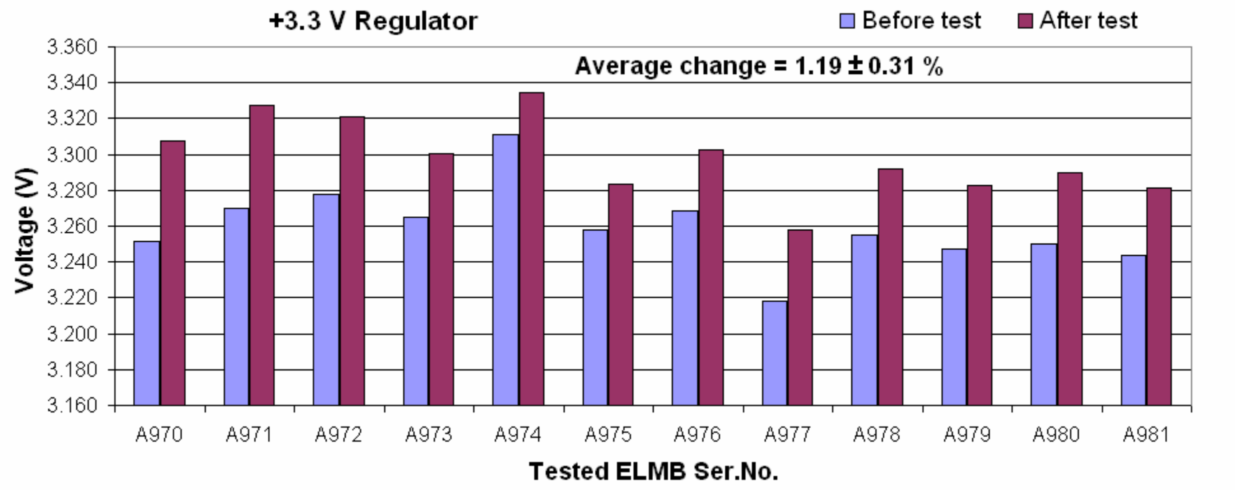

Figure 17 Changes in the 3.3V regulator

5.4 ADC readings

Figure 18 shows the change in the ADC readings in 5 channels. As a comparison three reference ELMB128 boards A982, A983 and A988 that were not subject to any radiation are shown. As seen the changes in the boards subject due to irradiation are negligible.

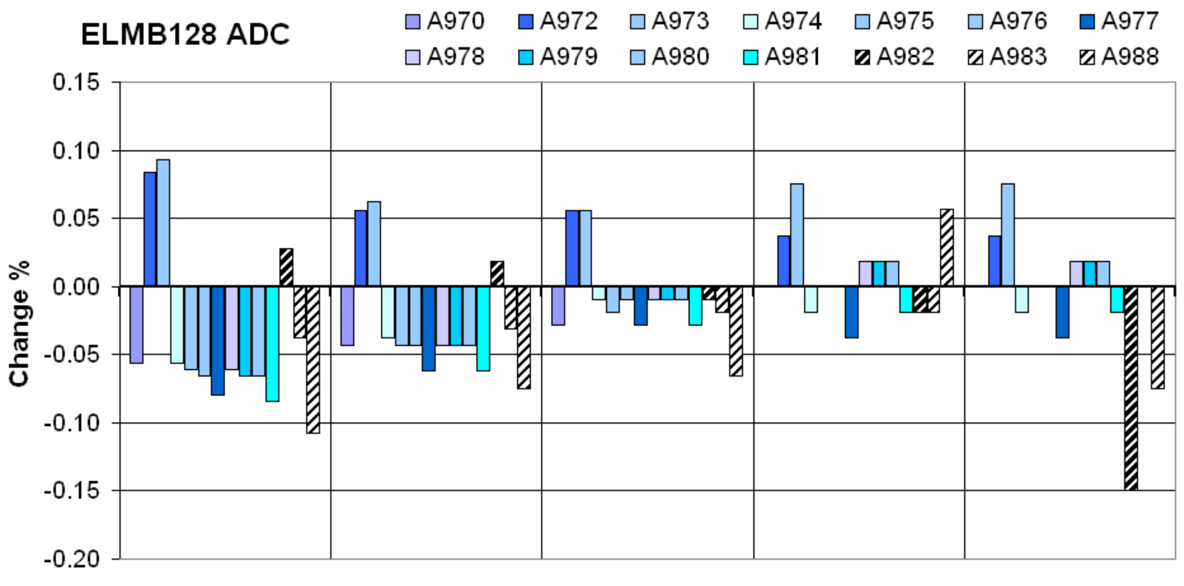

Figure 18 The change in the readings of 4 ADC channels for each ELMB.
The A982, A984 and A988 were not irradiated

6.0 Test of Agilent Technologies Optocouplers HCPL-0731

This dual channel optocoupler contains a separated pair of GaAsP light emitting diodes optically coupled to a pair of integrated high gain photo detectors. The current transfer ration is specified to be typically 1800 with min 400 and max 5000. It was discovered during the series production of the ELMB128 that one production lot of optocouplers received (with the date code 333) had gains close to maximum specifications. The optocouplers were placed (not powered) in the proton beam during total duration of the tests. After the irradiation the gain of 333 lot is reduced to 29% respectively while the gain of lot 527 to 89% of the originally value but still within the specifications, see Figure 9. The speed of both series increased as seen in Figure 10.

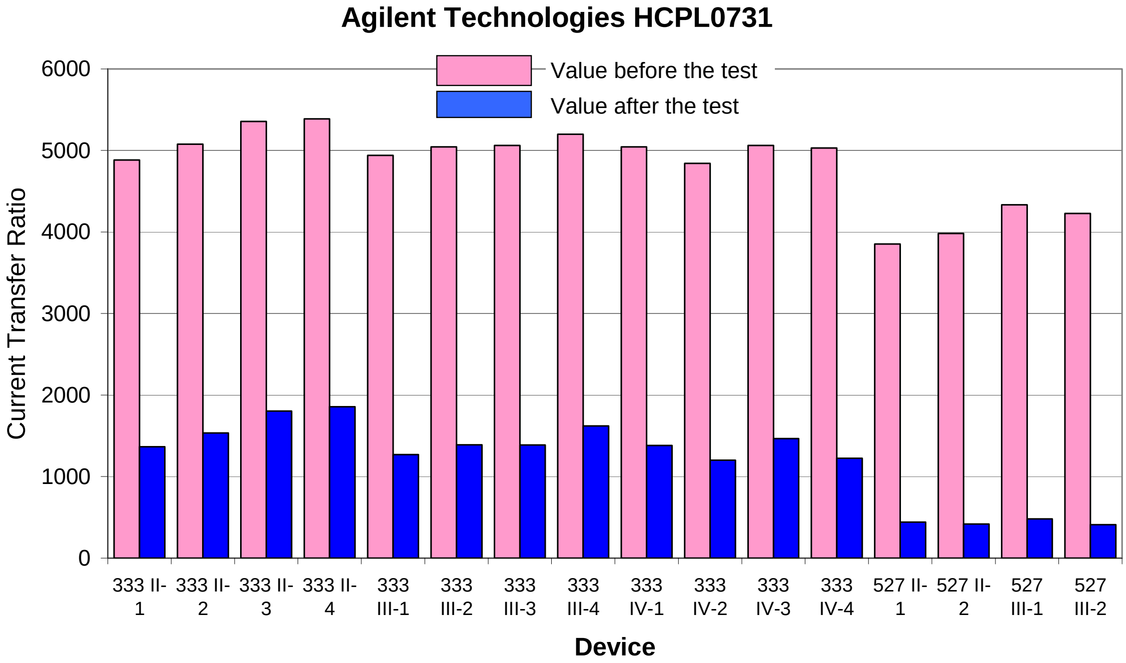

Figure 9 Change in the current transfer ratio after1.2$*10^{12}$ protons/cm^2

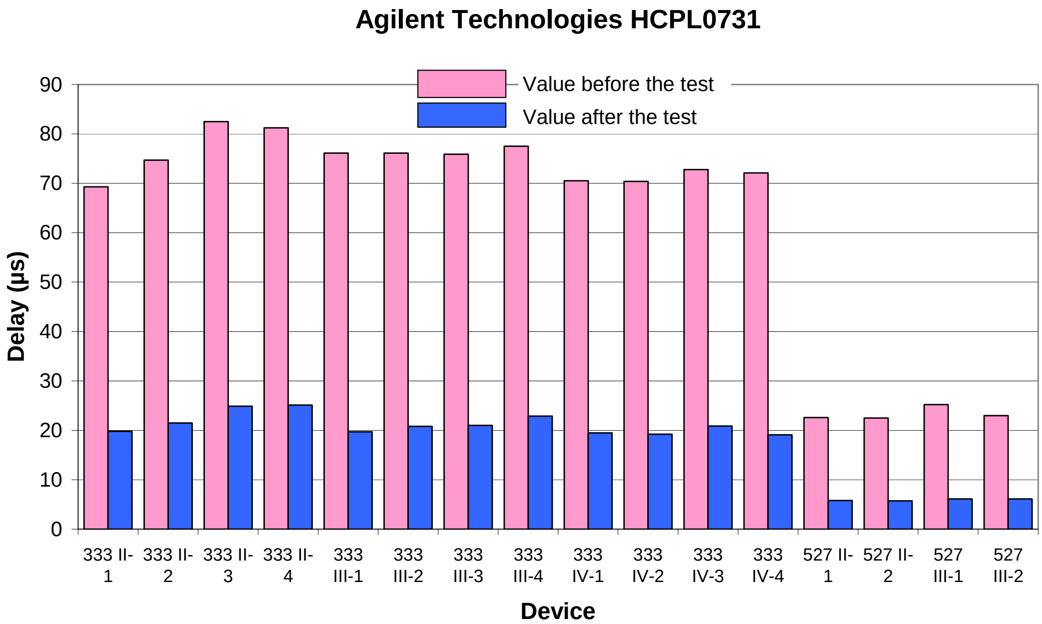

Figure 10 Change in delay of optocouplers for a fluence of 1.2$*10^{12}$ protons/cm^2

7.0 Conclusion

Twelve ELMB128 boards fabricated with samples of the components from the series production were tested for TID and SEE effects. Each of the board received an irradiation with 60 MeV protons to a fluence of $1*10^{11}$ protons/cm^2 corresponding to a TID of 140 Gy. The average fluence for 1 functional SEE error is in average $4.0*10^{11}$ protons/cm^2.

No current increase or significant change of any other parameter was detected after 140 Gy However one of the board failed in the re-programming of the flash memory after having received a flux of $5*10^8$ protons/s*cm2 and TID dose of 140 Gy.

The current transfer ratios of Agilent HCP-0731 optocouplers were reduced but are still within the specification after an irradiation of $1.2*10^{12}$ protons/cm^2. The speed of optocouplers increased.

References

[1] For a detailed technical description see: https://edms.cern.ch/document/348201/1

[2] http://www.cyc.ucl.ac.be/

[3] H.Boterenbrood, H.J.Burckhart, B. Hallgren and H. Kvedalen, ' Single Event Effect Test of the Embedded Local Monitor Board', CERN ATLAS Internal Working Note, DCS- IWN12, 8 March, 2001

[4] H.Boterenbrood and B. Hallgren, ' SEE and TID Tests of the Embedded Local Monitor Board with the ATMEGA128 processor', CERN ATLAS Internal Working Note, DCS-IWN20, 29 September, 2003

[5] H. Boterenbrood, ' ELMBio-rad (v4.2), version for Radiation Test ', version 1.1, NIKHEF, November 2003, http://www.nikhef.nl/pub/departments/ct/po/html/ELMB/ELMB-test-objects-v42.pdf

Appendix 1 List of all the Single Event Effects detected during the functional test

Item	Serial number of ELMB[1)]	Number of soft SEEs	Recovery after power cycle reset (Y/N)[2)]	Recovery after software reset (Y/N)[2)]	Description detailed in section	Comments	
						Failure mechanism	Corrected by
1	A970	**0**	-	-	-		
2	A971	**0**	-	-	-		
3	A972	**1**	-	Y	3.1	ADC gain setting	Not done
4	A973	**0**	-	-	-		
5	A974	**1**	-	-	3.2	ATmega128 (test EEPROM)	Auto recovery
6	A975	**0**	-	-	-		
7	A976	**0**	-	-	-		
8	A977	**0**	-	-	-		
9	A978	**1**	Y	N	3.3	ATmega128 (program loop)	Power cycling
10	A979	**0**	-	-	-		
11	A980	**2**	-	-	3.4	2 CAN Error messages	Auto recovery
12	A981	**0**	-	-	-		

1) Fluence received by each ELMB board was $1{*}10^{11}$ protons/cm^2

2) Y: successful operation- N: operation failed- minus sign: no operation was performed.