Irradiation Measurements of the Hitachi H8S/2357 MCU.

A. Ferrando[1], C.F. Figueroa[2], J.M. Luque[1], A. Molinero[1], J.J. Navarrete[1], J.C. Oller[1]

[1] CIEMAT, Avda Complutense 22, 28040 Madrid, Spain
[2] IFCA, Avda de los Castros s/n, 39005 Santander, Spain
jj.navarrete@ciemat.es

Abstract

This paper focuses on describing irradiation tests of Hitachi H8S/2357 microcontroller unit (MCU) and analysing the obtained results. Total Ionizing Dose (TID) and Single Event Effects (SEE) tests have been performed to determine the device radiation tolerance.

Firstly, four MCUs were exposed to a gamma source and a TID of 63 Gy was absorbed. No changes were detected.

Secondly, an integrated fluence of $4.1 \cdot 10^{11}$ protons·cm^{-2} was reached using 9 MCUs. The increase of the power supply current versus TID was obtained and a total of 811 bit upsets were detected in the SRAM memory during proton irradiation. Other SEE type was not detected.

This MCU will be used as an important component of the CMS link alignment system electronics and shows a very good radiation tolerance that exceeds the radiation tolerance criteria.

I. INTRODUCTION

This paper describes two irradiation tests of the Hitachi H8S/2357 microcontroller unit (MCU) and analyses the obtained results. Total Ionizing Dose (TID) and Single Event Effects (SEE) tests have been performed to determine the radiation tolerance of this device.

The Hitachi H8S/2357 is a powerful CMOS microcontroller, built around the H8S/2000 CPU and equipped with peripheral functions on-chip [1]. HD64F2357F20 was the F-ZTAT version used during irradiation measurements.

This MCU will be used as an important component of the CMS link alignment system electronics and it will be placed in the experimental hall, above the barrel (Z=3 R=10). In that area, the calculated levels of radiation are a fluence of $2.9 \cdot 10^{7}$ for charged hadrons (E>5MeV) and a maximum TID of 43 Rads/10y [2]. In these simulated levels no safety factor has been included. TID, Single Event Upsets (SEU) and Single Event Latch-ups (SEL) tests must be achieved for CMOS devices place at that location.

The gamma irradiation of four devices was performed on February 2003 at the IR14 facility of CIEMAT (Spain) [3]. This facility has two gamma sources, ^{137}Cs and ^{60}Co. The ^{137}Cs source emitting 0.662 MeV photons was used during experiments. Approximately, a TID of 63 Gy was reached during three sessions. Anomalies in MCU behaviour were not observed.

The proton irradiation of ten devices was performed on March 2003 at the CYClotron of Louvain-la-Neuve (CYCLONE) of the Université Catholique de Louvain, in Belgium [4]. The test was focused on study SEEs but some TID measurements were also available, in particular, the increase of the power supply current as a function of total ionizing dose was obtained. An integrated fluence of $4.1 \cdot 10^{11}$ protons·cm^{-2} was obtained with 9 MCUs. During those irradiation tests, only SEUs in SRAM were observed.

The remainder of this paper is composed of four sections. Section II presents a description of test electronic set-up. After that, Section III focuses on the test achieved at IR14 facility and the analysis of the obtained data. Section IV describes the tests conducted at CYCLONE and analyses the resulting data from these experiments. Finally, Section V concludes this paper.

II. GENERAL ELECTRONIC SET-UP

The electronic set-ups used in both tests are very similar and consist of: a portable computer, several data acquisition modules (DAM), a temperature sensor, two electronic boards and a +12V power supply. A schematic diagram of the system is presented in Figure 1. The differences between gamma system and proton system are marked with brackets. (1) indicates the type of link used between portable computer and electronic boards. In gamma test a RS-232 was used and a RS-422 link was utilized during proton test. (2) is the number of DAM used in the beam area. In the gamma test this number was 4 and in the proton test was 3.

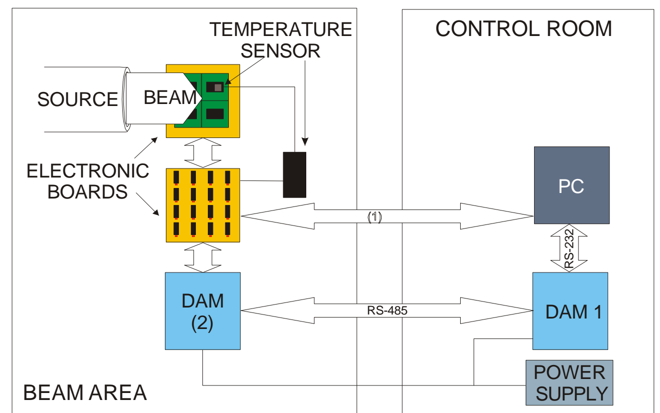

Figure 1: Electronic set-up

To avoid misunderstandings in the analysis stage of the data obtained during irradiation measurements, a specific

electronics was developed in two boards in order to separate electronic devices to be irradiated from those to be preserved from radiation. In this way, all observed effects produced by radiation could be attributed to MCU. One of the boards was designed to plug up to four microcontrollers and the other one contains the necessary electronic interface. Microcontrollers have a FP-128 package and are assembled in a PC board to make easier the prototyping phase and the MCU changing during irradiation tests. Photography of electronic card is showed in Figure 2.

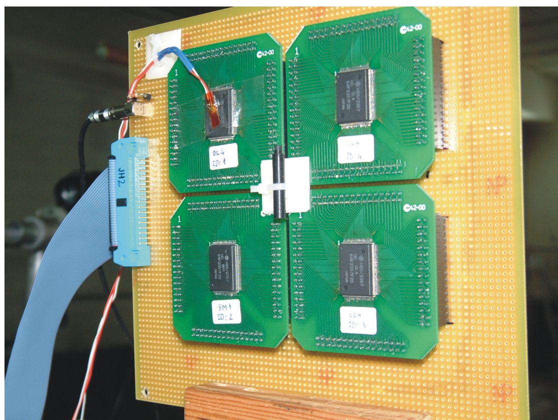

Figure 2: MCUs board.

The data acquisition modules measure the power supply current, a reference voltage used by MCU ADC, the MCU supply voltage, the temperature of one MCU (the temperature sensor stuck on MCU can be seen in Figure 2) and the frequency of an arbitrary signal generated by the MCU. A RS-232 to RS-485 converter module (DAM 1) connected portable computer with the DAMs.

A SCADA application, running on the portable computer, was used as the data acquisition system. That application was responsible for sending commands to data acquisition modules and MCU, receiving the data, representing the information on screen and storing it in different files.

III. GAMMA TEST

Four H8S/2357 with the series number 1 to 4 were tested simultaneously. The MCUs board was exposed to a gamma beam at the IR14 facility of CIEMAT (Figure 3).

A. *Experimental set-up*

A source of ^{137}Cs emitting 0.662 MeV photons was used during gamma test. The microcontrollers were placed at a distance of 92 cm from the source, where the beam diameter is 14.5 cm and the dose rate 3,81 Gy/h. Operative rules of facility and the low dose rate forced to divide the irradiation period in three sessions. The sessions took place during three consecutive days on February 2003. During the first session, with a duration of 300 minutes, a TID of 19.05 Gy was reached without significant changes in the MCUs behaviour. The second session lasted 360 minutes. Again no changes were observed with a total dose of 41.91 Gy. The last session had a duration of 341 minutes. The total TID of the three sessions was 63.56 Gy and the MCUs did not present important changes.

Figure 3: IR14 facility

B. *Gamma test results*

1) Power supply current

The test was focused on the supervision of power supply current. This current was monitored before the test, during irradiation and during an accelerated aging test accomplished after irradiation. Table 1 displays these results. Though current changes produced by different MCU workloads were noticed during monitoring, a representative current variation was not observed and the power supply current increase can be rejected at the TID level reached with this test.

Table 1: Power consumption

	Power supply current (mA)			
	MCU 1	MCU 2	MCU 3	MCU 4
Before irradiation	69.545	68.355	70.221	69.112
During irradiation	71.007	69.26	70.65	70.686
During aging	68.311	68.026	68.318	68.272

2) ADC read-out

Other study achieved during irradiation was the monitoring of MCU ADC. Constant DC voltages were applied to six analog ADC inputs. These voltages were derived from a reference voltage through a resistor network. Six ADC channels were chosen because it is the maximum number of channels that is expected to use.

The resolution of the ADC is 10 bits, the maximum conversion time is 6.7 µs and the absolute precision (the deviation between the digital value and the analog input value) is ±4 LSB for the following conditions: $V_{CC} = AV_{CC} = 5.0$ V, $V_{ref} = 5.0$ V, $V_{ss} = AV_{ss} = 0$ V, F = 20 MHz and T_a = -20 to +75 ºC.

During irradiation, an increase in the standard deviation values was observed in relation to the data obtained before irradiation but there was not a considerable change in the mean of ADC conversion data. The changes between means

of ADC channel read-outs before and during irradiation were less than absolute precision of ADC.

3) Frequency measurement

In order to validate the MCU 16-bit timer, each MCU generated a square signal with a frequency of 11421 Hz approximately. This frequency value was chosen because it can be useful in some optical sensor applications. The frequency of this signal was measured before irradiation, during irradiation test and during accelerated aging test. The resolution of data acquisition module used to measure this frequency was 1 Hz. Only two frequency values took place, 11421 Hz and 11422 Hz. Figure 4 shows the mean and 95% confidence interval of the frequency online measurement.

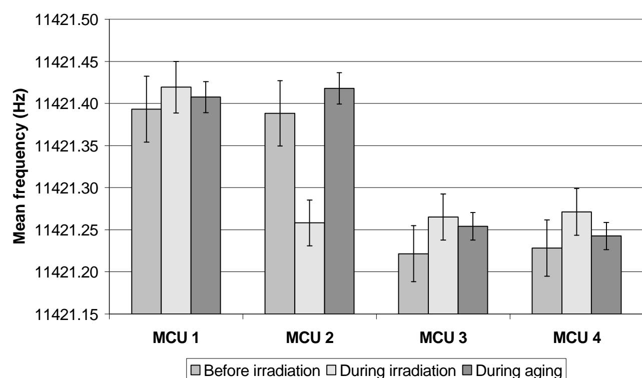

Figure 4: Mean frequency and 95% confidence interval of the signal frequency during gamma irradiation

4) Flash Memory Reprogramming

After each gamma irradiation session, the four MCUs were reprogrammed. No problems in the flash memory programming function were noticed.

IV. PROTON TEST

Ten H8S/2357 with the series number 5 to 14 were tested successively. The MCUs were exposed to a 60 MeV proton beam at the CYCLONE facility of the Université Catholique de Louvain (Figure 5).

A. *Special features of electronic set-up*

The electronic arrangement with two boards separating electronic devices to be irradiated from those to be preserved from radiation was used. The interface board was redesigned. This new card includes the basic electronics to interface two MCUs with the measurement system. In addition, SELs were taken into account and current limit devices were introduced to avoid irrecoverable damage of MCUs (a current limit of 110 mA was set). Although electronic system was prepared to work with two microcontroller, only one was irradiated during each test. The same MCUs board used during TID at IR14 was utilized with only one microcontroller plugged.

Figure 5: CYCLONE facility

B. *Experimental set-up*

Table 3.1 shows the set-up for each MCU.

Table 2: Proton irradiation set-up

MCU	Fluence (protons·cm^{-2})	Test Time (s)	TID (Gy)
5-11	$1.53 \cdot 10^{10}$	500	21.42
12	$3 \cdot 10^{11}$	1000	420
13-14	$1.5 \cdot 10^{11}$	500	210

The first seven MCUs (5-11) were irradiated with the set-up indicated in Table 2. The high radiation tolerance exhibited by microcontrollers led to the modification of this set-up. There and then a new set-up was decided, it can be seen in Table 2 (MCU 12). The new plan goal was to obtain the increase of the supply current versus TID and improve the statistics on the occurrence of SEEs, until then only SEUs took place. During the irradiation of MCU number 12, the CYCLONE operator decided to adjust the beam because some stability problems had appeared. Those data test were ruled out because of the uncertainties in the measurement parameters introduced by that adjustment. Anyway, halfway through irradiation a fast increase of current was observed and the limit current set by the current-limited P-channel switch was reached, indicating that total dose deposited by protons right then was enough to obtain the current versus TID curve. This observation was used to determine the set-up of MCUs number 13 and 14.

An integrated fluence of $4.1 \cdot 10^{11}$ protons·cm^{-2} was reached, with the fluence of the eighth microcontroller discarded. In table 2, a conversion factor of 10^{10} protons/cm^2 = 14 Gy for 60 MeV protons was used to obtain TID [2].

C. *SEEs detection system*

The MCU was expected to be susceptible to SELs. SELs result in an increase of the current consumed by the microcontroller and then it can be damaged in an irreversible way. To avoid this situation a limit current device was

integrated in the design of the electronics. With this device, a maximum current limit of 500 mA can be set.

During proton irradiation an arbitrary current limit of 110 mA was set, the power supply current in normal operation is 70 mA. A digital I/O DAM was used to supervise the fault indicator and control the switch on/off input of the limit current device. This control signal allows resetting the MCU from computer application. Automatic detection of SELs and control of switch on/off input was implemented in application.

The MCU comprises memories and register that are particularly vulnerable to SEEs. It includes 128 Kbytes of flash memory, 8 Kbytes of SRAM and 291 bytes of registers. In order to detect SEEs in the memories and register, dedicated software was added to normal CPU application program. Basically, this program is command driven but it does some tasks automatically. On the automatic side, it checks 90 registers every second and serial communication interface registers every time it transmits something. By computer request it carries out the following tasks: ADC read-out; SEE test (4 Kbytes of SRAM, 90 registers, 64 Kbytes of flash memory and program code cyclic redundancy checksum are checked); specific memory address or register reading; specific memory address or register writing and whole flash memory test.

Some fault-tolerance mechanisms were included in MCU program. A watch dog timer was used and the three voting technique was employed in critical variables. Too, the tasks executed automatically by the MCU (registers checking) were developed to improve the system performance in the presence of faults caused by proton irradiation.

The application running in the portable computer sends to MCU the following command sequence every two seconds: read-out of 6 ADC channels, specific SRAM address reading (this address is generated randomly), specific flash memory address reading (random too) and SEE test. The sequence lasts less than a half of second. An automatic reset generation was implemented in this application for the following two cases: communication break and irrecoverable SEE. An automatic recovery procedure from SEL was developed too. On the other hand, the application allows reprogramming the MCU and generating user reset. In order to determine the irradiation periods, the application records starts and stops of MCU program execution.

D. SEE test results

1) SRAM test

The test involved 4 Kbytes of the SRAM from a total of 8 Kbytes. A total of 811 SEUs were detected during the tests of 9 MCUs (data from MCU number 12 were rejected). Figure 6 shows the total number of SEUs detected versus fluence. The least-squares regression line is used to obtain a cross-section of $4.9 \cdot 10^{-13}$ SEEs per byte and protons·cm^{-2}.

Only single bit upsets were produced. Figure 7 displays the distribution of these flips per bit. The figure shows that the SEUs were distributed evenly over the different bits. The distribution between changes from 0 to 1 and from 1 to 0 can be considered even too. If the bit flips of MCU number 12 are included, the idea of an even distribution per bit and per change type is reinforced.

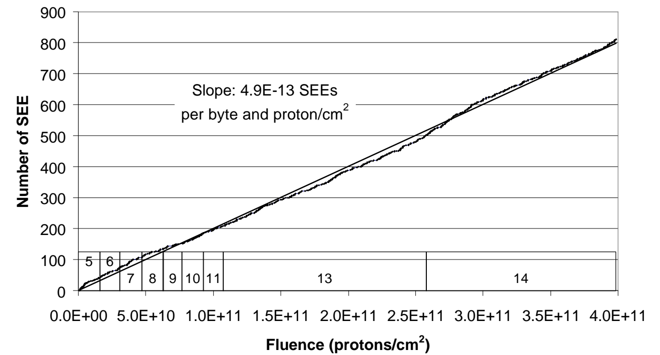

Figure 6: Number of SRAM SEEs versus fluence

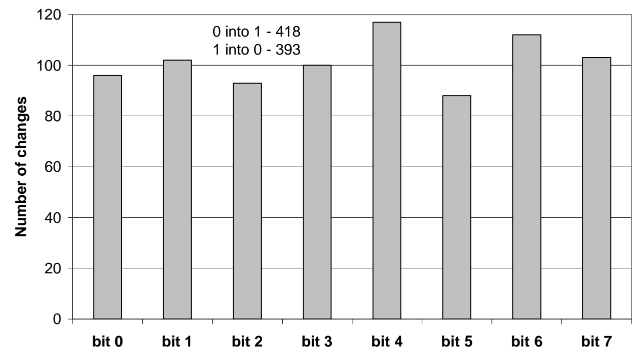

Figure 7: SRAM upset distribution per bit

2) Flash memory test

During irradiation test cyclic 64 Kbytes flash memory checking and CRC (Cyclic Redundancy Checksum) of code program were achieved. A 128 Kbytes checking and reprogramming was performed after test. No changes were detected and a successful reprogramming took place. Considering the whole memory, one error would correspond to a cross-section of $1.9 \cdot 10^{-17}$ SEEs per byte and protons·cm^{-2}.

3) Register test

The test involved 90 register bytes of a total of 291. No SEEs were detected. Supposing one error, the cross-section would be $2.7 \cdot 10^{-14}$ SEEs per byte and protons·cm^{-2}.

4) Result summary

The Table 3 presents the obtained results during SEE test. The fluence used to calculate the cross-sections is $4.1 \cdot 10^{11}$ protons·cm^{-2}.

Table 3: Summary of SEE test results

	Number of bits tested	Number of SEEs	Cross-section cm^2/bit
SRAM	32768	811	$6 \cdot 10^{-14}$
FLASH	1048576	<1	$<2.3 \cdot 10^{-18}$
Registers	720	<1	$<3.4 \cdot 10^{-15}$

E. TID effects

1) Power supply current

The MCU power supply current was measured online during the proton tests. As in TID tests, MCU5-MCU11 currents did not present important changes.

The increase of power supply current as a function of TID (fluence) is shown in Figure 8. Although the statistics are very limited because only the irradiation results of two devices at high fluence values are considered valid, a light increase in current consumption can be observed from an $8{\cdot}10^{10}$ protons$\cdot$cm^{-2} fluence. A faster increase of this current was noticed from 10^{11} protons$\cdot$cm^{-2} fluence. During MCU 14 proton irradiation, the current limit (110 mA) was reached. This situation is displayed in Figure 8. In any case, the increase of current happens at a fluence value a lot higher than expected fluence.

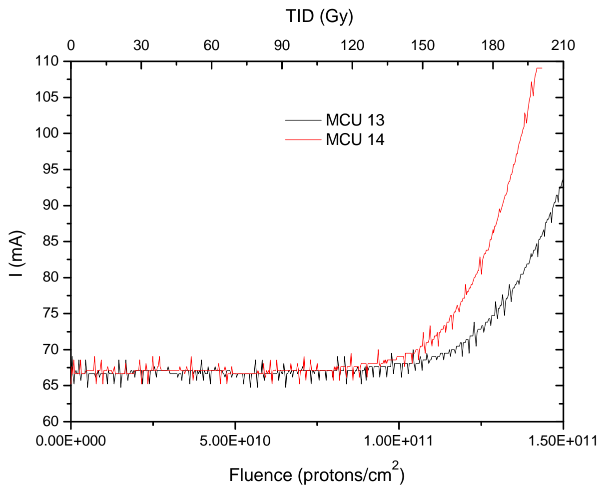

Figure 8: Power supply current of MCUs 13 and 14 during proton irradiation

2) ADC read-out

During proton test, the ADC read-out set-up was identical to that used in gamma test. Constant DC voltages were applied to six analog ADC inputs. A resistor network was used to obtain these voltages.

The ADC channel read-outs before irradiation and during irradiation presented a high stability in all channels. Before irradiation the standard deviation was less than 0.2 LSB (1 LSB = 4.88 mV) and no change can be observed during irradiation.

3) Frequency measurement

Frequency measurement set-up was identical to that used in gamma test. Figure 9 displays the mean and 95% confidence interval of the frequency online measurements. High frequency stability was observed during irradiation.

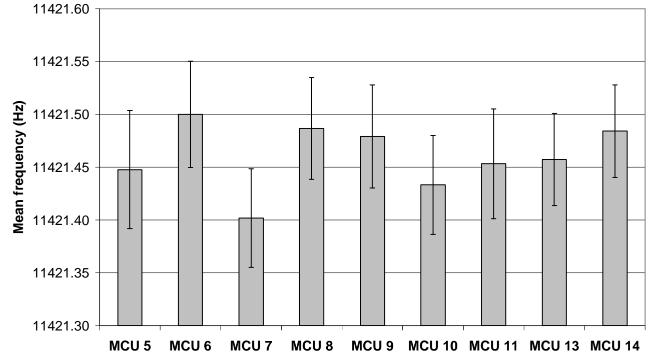

Figure 9: Mean frequency and 95% confidence interval of signal frequency during proton irradiation

4) Flash memory reprogramming

This function was not influenced by radiation and all MCUs could be reprogrammed after proton test.

V. Conclusion

The levels reached during gamma and proton tests (TID of 210 Gy and fluence of $1.5{\cdot}10^{11}$ protons$\cdot$cm^{-2}) have exceeded the radiation tolerance criteria, including safety factors, and the Hitachi H8S/2357 microcontroller has showed a very good behaviour. No malfunctions were detected during TID tests and a total dose of 145 Gy was necessary to note a fast power supply current increase. During proton test, only bit upsets in SRAM memory were detected. Flash memory or register SEEs were not detected. In the same way, SELs were not produced.

In order to improve SEEs statistics, mainly SELs and register SEUs, new tests have to be accomplished. Likewise, an improvement in the statistics of the increase of power supply current as a function of total ionizing dose has to be obtained.

References

[1] "H8S/2357 Series, H8S/2357F-ZTAT™ Hardware Manual", Hitachi 1997.

[2] "A global radiation test plan for CMS electronics in HCAL, Muons and Experimental Hall", Updated Draft 17/12/1999.

[3] http://www.ciemat.es/instalacion/0i078.html

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