ESA-QCA9930S-C

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2 DEC 1996

TEST REPORT

Protons Testing of
CS5101A

This Test Report has been prepared for:

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Ref. : HRX/96.1997.
Issue : 1
Date : Nov 21, 1996

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1. INTRODUCTION

This report presents the results of the protons evaluation test of Crystal CS5101A 16-bit A/D Converter which has been performed using the Proton Irradiation Facility of Paul Scherrer Institut in Viligen, Switzerland.

Prior to this test, this device has been characterized to the heavy ions environment with the following results:

- SEU LET threshold of 1,45 MeV/mg/cm² (C 12)
- Latch-up LET threshold of 11.6 MeV/mg/cm² (Cl 35)

The aim of this test was to assess the sensitivity of the CS5101A to SEUs induced by protons as well as the sensitivity of the circuits to latch-up.

Both test results and event rates computations are presented in this report.

2. APPLICABLE DOCUMENTS

The following documents are applicable:

- Protons test plan No. PO-PL-TLG-PL-1325, dated 9/09/96.

2.1 REFERENCE DOCUMENTS

- Crystal Semiconductor Data Acquisition Databook, CS5101A data sheet.
- Single Event Effects Test Method and Guidelines ESA/SCC basic Specification No 25100
- Paul Scherrer Institut Users Guide

3. ORGANIZATION OF ACTIVITIES

The different tasks performed during this evaluation have been conducted in the order shown in Table 1 by the relevant company.

Table 1- ORGANIZATION of ACTIVITIES

Para. 5.1	Procurement of Test Samples	Tecnologica
Para. 5.2	Preparation of Test Hardware and Test Program	Hirex
Para. 5.3	Samples Check out	Hirex
Para. 5.4	Accelerator Test	Hirex
Para. 5.5	Chip Identification (opening of 1 device)	Hirex
	Protons Test Report	Hirex

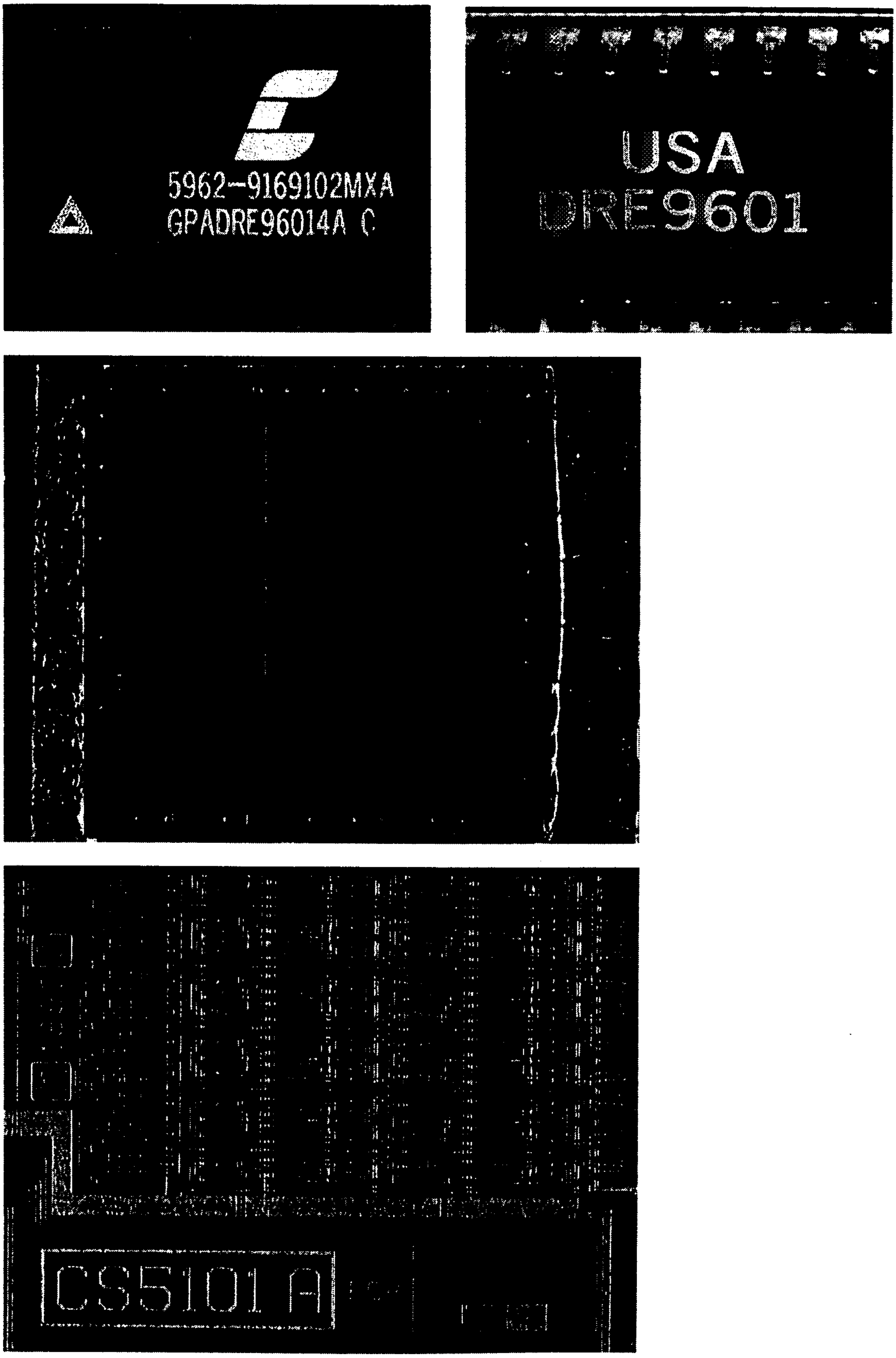
4. DEVICE AND MANUFACTURER INFORMATION

Description of the devices is as follows:

Part type :	CS5101A	
Manufacturer :	Crystal Semiconductor	
Package :	28-Pin Frit Sealed Ceramic Dual In Line	
Quality Level :	Not available	
Date Code :	9601	
Marking :	Top side: Crystal Logo	5962-9169102MXA GPADRE96014A C
	Bottom side:	USA DRE9601
Serial Number :	#11, #12, #13, #14, #15	
Die Size :	6.8x6.8 mm approximately	
Die Marking :	CS5101A M 1990 C	
Tested samples :	#11, #12, #13, #14, #15	

External and Internal Photos are shown in Figure 1.

Figure 1 External and Internal Photos



5. TASK DESCRIPTION

5.1 PROCUREMENT OF TEST SAMPLES

5 samples have been procured by Tecnologica, and provided to HIREX.

Devices serial numbers: #11, #12, #13, #14, #15

5.2 PREPARATION OF TEST HARDWARE AND TEST PROGRAM

Overall device emulation, SEU and Latch-up detection, data storage and processing have been previously implemented for the heavy ions test campaign, using a standard test hardware and an application specific test board. No specific change was foreseen for the protons test campaign.

The standard test equipment was the « STAM » piece of hardware developed under CNES license and currently used by the CNES Parts Department test team for testing devices of similar complexity. This equipment is driven by a PC computer through a RS232 line. All power supplies and input signals are delivered and monitored by the STAM equipment which also stores in its memory the output data from the device throughout the specific test board.

The application specific test board allowed to interface the standard test hardware with the device under test, in order to correctly emulate the relevant part, to record all the different type of errors during the irradiation and to set output signal for processing and storage by the standard test equipment.

At the end of each test run data are transferred to the PC computer through the RS232 link for storage on hard disk or floppies.

The detailed principle of the test is described in § 7.

Schematic of test board is shown in Figure 2.

5.3 SAMPLES CHECK OUT

A functional test sequence has been performed upon reception of the devices by Hirex engineering.
The main outcome when these devices were checked on the test board is that the noise level is higher than the one measured with the parts used for the heavy ions campaign. The consequence was that only 13 bits could be monitored during the proton test (mask FFF8).

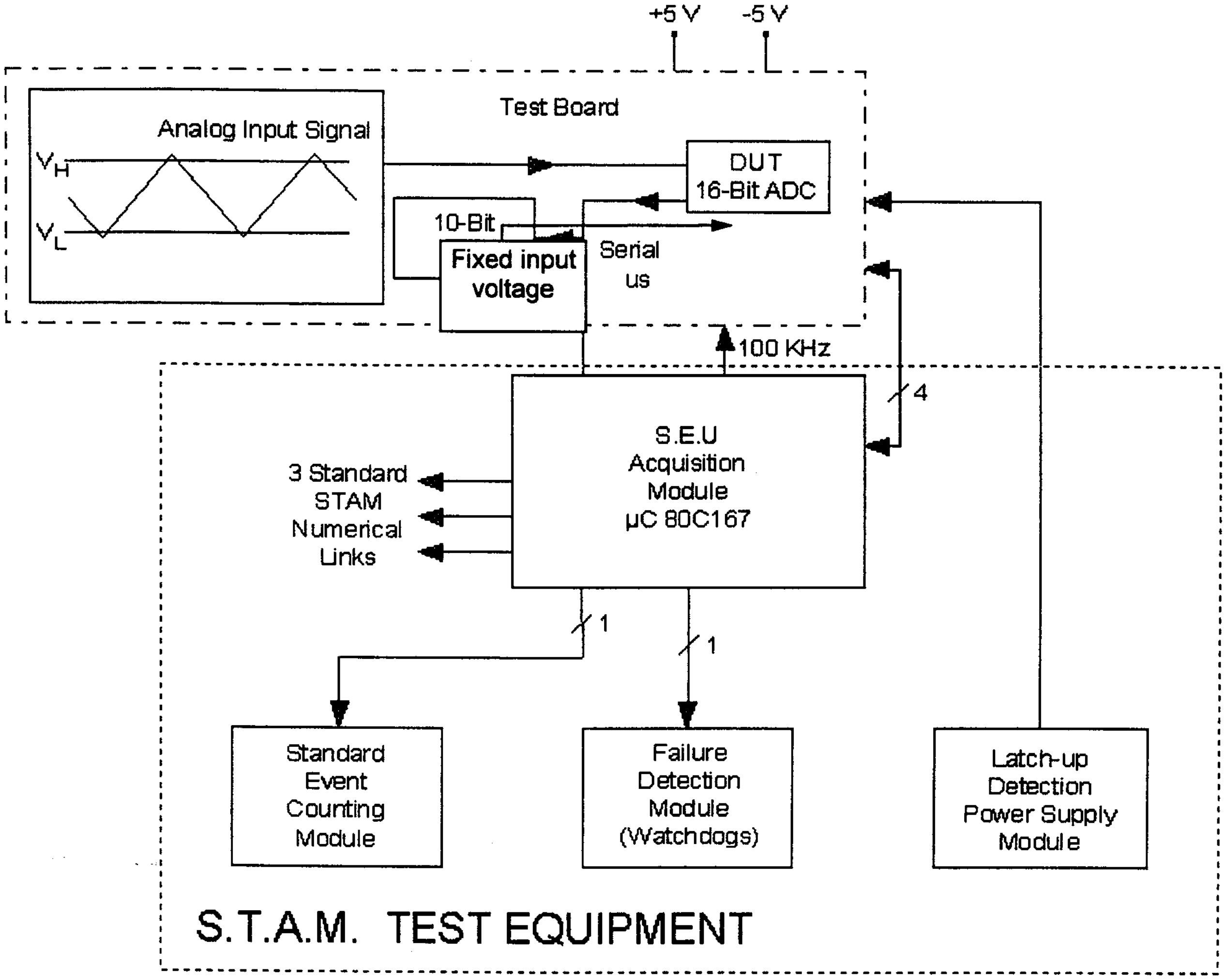
5.4 ACCELERATOR TEST

Test with protons accelerator was performed at Paul Scherrer Institut (PSI) in Viligen (Switzerland) under HIREX Engineering responsibility.
The 5 samples were irradiated in order to take care of the induced total ionizing dose received per device.

5.5 CHIP IDENTIFICATION

One device has been delidded by HIREX using a ceramic opener for this purpose.

Figure 2 - CS5101A TEST BOARD SCHEMATIC



6. **Proton Irradiation facility (PIF)**

The following information is from the PSI users guide:

The Proton Irradiation Facility (PIF) in the NA-hall was built in 1992 by the PSI Astrophysics Group under a contract with the European Space Agency. The main tasks of PIF are to study proton induced effects on semiconductors, materials and man. As PIF should provide reliable information on effects caused by cosmic radiation in satellite electronics and devices, emphasis is given to generate realistic proton spectra encountered by spacecrafts in any possible orbit. The facility serves, however, not only for the irradiation of electronic components; PIF has been specially designed for a wide range of applications. The characteristic features of the facility are: broad range of energies and intensities of the proton beam; fast and uncomplicated experimental set-up; flexibility towards user requirements; and user-friendly operating systems. Experiments in solid state physics and atmospheric physics can be performed, as well as tests of particle detectors (e.g. CCDs), radiation monitors and technologically novel semiconductors.

PIF investigations cover the following fields:

- studies of the radiation hardness of electronics;
- basic research on radiation effects in semiconductors;
- development of radiation monitors for space applications;

- tests of new, radiation-hardened technological products;
- performance studies of modern instruments, like SQUIDs, CCDs etc., in the radiation environment;
- investigations of isotope production rates for atmospheric physics;
- studies of biological effects for radiation protection purposes;
- calibration of detectors for high energy physics and satellites.

The proton beam for PIF is delivered by the 590 MeV Ring accelerator with the help of the electrostatic beam splitter, which deflects between 1 and 20 uA of the beam into the NA-hall (see Fig. 3.21). After the PIREX target station, the beam passes through a set of exchangeable copper-graphite blocks (PIREX degrader), reducing its energy and intensity, and is guided to the NA2 and PIF areas. The PIF experimental set-up consists of the local PIF energy degrader, beam collimating and monitoring devices, and a movable X-Y table with the sample holder (see Fig. 6.1). The maximum allowed energy is 300 MeV; the current at this energy is limited to 3 nA not to activate the experimental area.

Irradiations are usually carried out in air. According to experience and user requirements, the monitor detectors are selected for each experiment individually (ionisation chambers, PIN diodes, plastic scintillators). The irradiation is controlled through a set of scalers and a PC-based data acquisition system. The system monitors the flux of protons, calculates deposited dose and controls the position of the sample and beam focus parameters. It also allows for setting the beam energy with the help of the PIF energy degrader. This allows to perform fully automated irradiations with arbitrary proton spectra.

Main characteristics of the facility:

- Standard proton energies (after the PIREX degrader): 300, 254, 212, 150, 102 and 60 MeV, accurate to within 1%;
- Energies available using the PIF degrader: quasi continuously up to 300 MeV - see Fig. 6.2;
- Energy straggling after the PIF degrader for 300 MeV initial beam typically 7.2 MeV at 200.0 MeV and 15.4 MeV at 50.0 MeV - see Fig. 6.2;
- Upper limit of the beam intensity at 300 MeV: 3 nA (0.5 nA at 50 MeV); the minimum intensity can be set as low as a few protons/s;
- Maximum flux-dose rate at the beam centre for 300 MeV: 2.5 x 107 protons x cm-2s-1 - 1.2 red so-1 (0.012 grey s-1 with 1 uA beam at PIREX;
- Beam profile at 300 MeV: Gaussian-like with 0 = 2 cm. It can be flattened by defocusing the beam;
- Irradiated sample area: 10x10 cm2 or smaller, depending on collimators and defocusing;
- Neutron background: less than 1 0-4 neutron /proton x cm2;
- Accuracy of the flux-dose determination: 5%.

The PIF operates as a main user or in parasitic mode with the PIREX experiment. Because day shifts are usually reserved for biomedical applications, PIF runs mainly at nights and during weekends.

7. TEST PATTERN DEFINITION FOR PROTONS TEST

7.1 OPERATING CONDITIONS AND UPSETS AND LATCH-UP DETECTION

The test principle used is as follows:

Due to the lack of access to the different areas of the DUT circuit, it was not possible to make the distinction between upsets occurring within the serial output buffer register and the ones occurring during the conversion algorithm.
In the same way, upsets occurring in the calibration SRAM may only be detected if, as a result, they induce missing codes in the output words, i.e. a change in the weight of a given bit higher than an LSB (According to CRYSTAL data sheet, each bit is weighted with a 18-bit precision at the end of the calibration phase).

Latch-up: Both transient and true latch-up were monitored and recorded and consequences of a transient on the device operation have been investigated.

Calibration phase: this phase lasts 11,528,160 master clock cycles, and cannot be monitored during the execution. One calibration cycle is performed in absence of ion beam, followed by the acquisition of the fixed input voltage, then the device undergoes continuous calibration cycles under irradiation, followed by the measure of the fixed input voltage, in order to compare with the initial one.

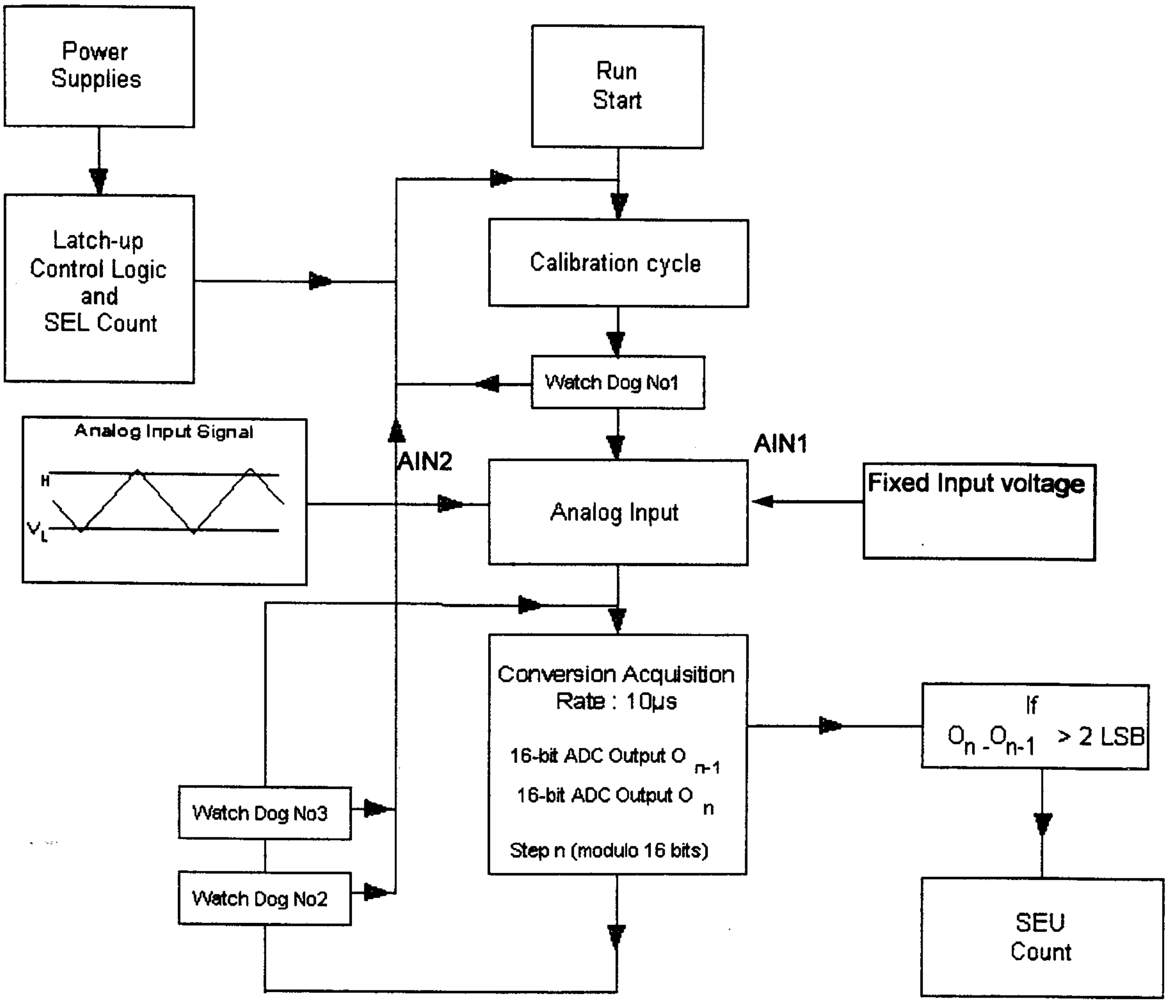
Run duration is adjusted in function of the available flux and the fluence to be achieved.

On channel 2, the analog input consists in an up and down voltage ramp with an half period of about 6.5 s, generated by an analog integrator with a slope of 0.1 LSB per 10 µs. This will allow to sweep over all the digital output codes without triggering the SEU counter: Every 10 conversion cycles, the output word will be incremented/decremented by 1 LSB which is below the 2 LSB threshold of the SEU detection.
On channel 1, a known fixed input voltage is applied (Vref minus few LSBs)
Watchdogs are used to prevent the consequences of eventual functional failures which could place the DUT under uncontrolled conditions:

- Watch Dog No 1: If calibration time of the DUT exceeds a given threshold, then a new calibration cycle is initiated (RESET)
- Watch-Dog No 2: If no end conversion signals are detected during Tbd consecutive conversion cycles, then RESET
- Watch-Dog No 3: If 10 consecutive conversion errors on any channel, then RESET

Refer to figure 3 for more information.

Figure 3 - CS5101A TEST SEQUENCE



During the test, DUT power supplies are monitored to detect any current increase which would indicate that the DUT is stuck in a latch-up mode; power-off / reinitialization is performed via the software program used with STAM equipment. It should be noted that during latchup sequencing and device calibration sequence, the device was automatically shielded with an aluminum screen synchronized with each latchup detection

7.2 SELECTION OF TEST CONDITIONS

7.2.1 CS5101A Theory of Operation

The CS5101A implements the successive approximation algorithm using a charge redistribution architecture. Instead of a traditional resistor network, the DAC is an array of binary-weighted capacitors. All capacitors in the array share a common node at the comparator's input. Their other terminals are capable of being connected to AGND, VREF or AIN (1 or 2) (see Figure 3 « CS5101A functional block diagram).
When the device is not calibrating or converting, all capacitors are tied to AIN.
To achieve 16-bit accuracy from the DAC, the CS5101A use a self calibrating scheme. Each bit capacitor actually consists of several capacitors in parallel which can be manipulated to adjust the overall bit weight. An on-chip microcontroller precisely adjusts each capacitor with a resolution of 18 bits.
The CS5101A should be reset upon power-up, thus initiating a calibration cycle. The device then stores its calibration coefficients in on-chip SRAM. When the CS5101A is in power-down mode, it retains its calibration coefficients in memory, and need not be recalibrated when normal operation is resumed.

Free Run (FRN) mode of operation of CS5101A has been used during testing, in particular because this mode allows a more complete monitoring of internal logic circuitry and emulates a maximum of output signals. In this mode, the converter initiates a new conversion every 80 master clock cycles, and alternates between channel 1 and channel 2.

The CS5101A is controlled with a dedicated board including a DSP 80C167 from Siemens and associated circuits.
The CS5101A measures alternatively a fixed voltage and a ramp signal which allow a sweep on all the different 65536 codes.
Detected anomalies leading to circuit reinitialization are called « major events », they include the following:

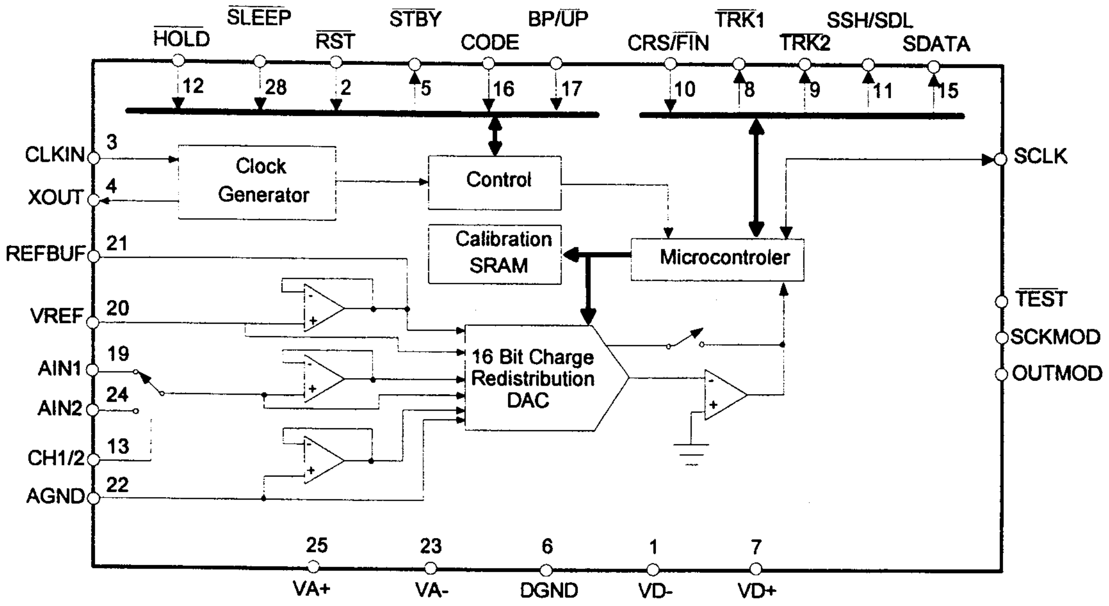
- #1- Latch-up detected by a current increase either on the positive power supply or on the negative one,
- #2- Calibration time exceeded,
- #4- Repetitive conversion error, for instance due to a change in the calibration RAM,
- #8- Conversion time exceeded.

Other anomalies are called « minor events », and correspond to:

- #16- Channel 1 conversion error (fixed value)
- #32- Channel 2 conversion error (ramp)
- #64 - Error on a logic signal (SCLK, TR1/TR2, SSH/SDL, CH1/2,...)

Major and minor events are recorded separately. STAM system interrogates microcontroller board every 10 ms that returns back to STAM categorized errors occurred since previous interrogation.

Figure 4- CS5101A FUNCTIONAL BLOCK DIAGRAM



8. EXPERIMENTAL TEST SET-UP

8.1 PROTON ENERGY SELECTION

According to the referenced test plan, the following protons energies have been considered:

50 MeV, 100 MeV, 150 MeV, 200 MeV.

300 MeV protons have also been used in addition.

Beam Energy MeV	Energy @Targe MeV	Alu Degrader mm	LET (for Si) MeV/cm
304,0	49,2	233,0	23,320
304,0	99,6	207,0	13,664
304,0	149,9	169,0	10,234
304,0	200,2	121,0	8,461
304,0	300,3	2,0	6,660

Table 2 - Characteristics of proton beams used

8.2 FLUX RANGE

Particle flux was comprised between 5. 10E6 and 7.5 10E7 /cm^2/sec under normal incidence.

8.3 PARTICLE FLUENCE LEVELS

Fluence level was comprised between 1. 10E10 and 1. 10E11 particles/cm^2 under normal incidence

8.4 DOSIMETRY

The current PSI dosimetry system and procedures were used.

8.5 ACCUMULATED TOTAL DOSE

The equivalent total dose (rad(Si)) received by the device under test was monitored via the current BNL Tandem standard procedure.
Cumulated total ionizing dose per run for each tested sample is shown in Table 3.

8.6 TEST TEMPERATURE RANGE

All the tests performed were conducted at ambient temperature.

9. Results

Test implementation:

As previously mentioned in paragraph 5.3 "functional check", this new sample presents a higher sensitivity to parasitic noise on the test board, when compared to the sample used for heavy ion test and only 13 bits can be monitored for both the fixed voltage reference and the voltage ramp.
This means that for both, masque FFF8 have been used.

The proton beams sequence and runs duration are as per table 3 here after.

It must be pointed out that due to the very low number of events observed, very high fluences were needed and the consequence was that the induced cumulative TID effects were not negligible. Between 5 to 7 krads, a significant increase of the device power consumption was observed and it was decided to stop the irradiation for each sample when power supply consumption started to increase significantly (even if the device was still operating properly). To check the validity of this assumption, sample #14 has been tested up to 10 krads. Around this level, the device starts to show continuous repetitive conversion errors.

Every two milliseconds the number of errors occurred is downloaded to the test unit memory. One has to keep in mind that a conversion cycle lasts 10 microseconds, and as a consequence, depending on the beam flux, several errors may be detected during this time frame.

Only one error maximum has been observed in each recording time frame of 2ms.

These errors are of two different types and are listed in table 3 here after:

Major error

It means that a reset of the DUT, followed by a calibration cycle is performed each time the monitoring system detects a major error.

Chronic error is when 10 consecutive conversion errors occurred, for instance due to a change in the internal calibration RAM. This is considered as a major error and, then a reset plus a calibration cycle is performed.

Minor error

It means that the monitoring system does not trigger any subsequent action on the DUT.

Both ref. voltage and ramp voltage single conversion errors have been observed which are considered by the monitoring system as minor.

The error shift recorded for each type was between 8 points and 32 points maximum.

The corresponding cross-section is computed with the total number of errors per run and is also given in Table 3.

The results are plotted for the different pieces on Figure 5.

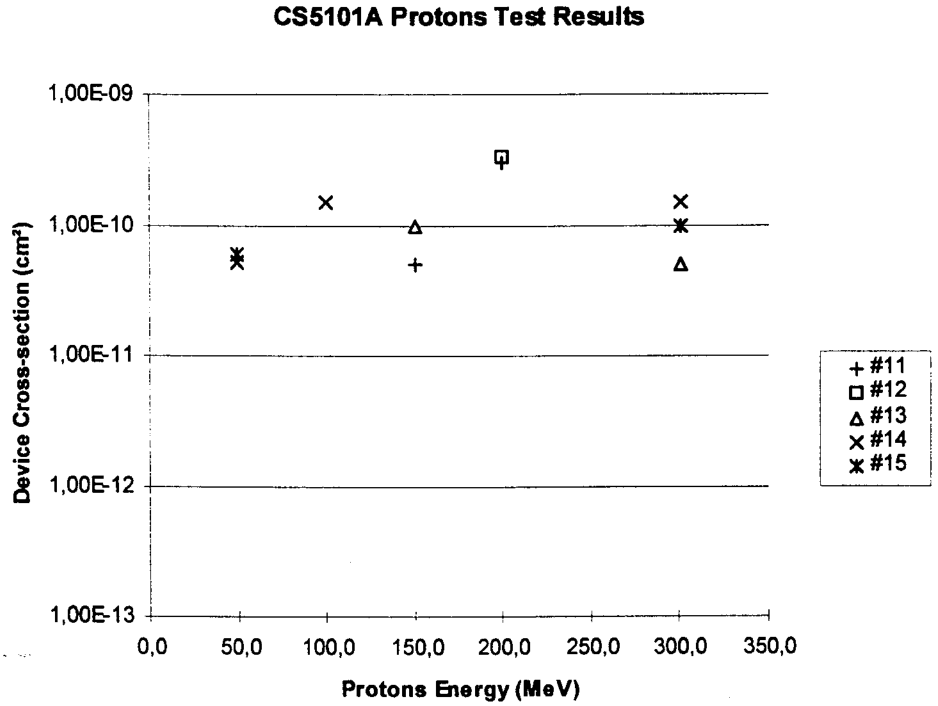
9.1 LATCH-UP

Latch-up is detected each time any of the 2 power supply currents, exceeds 90 mA.
No latch-up has been detected at any proton energy.

Table 3 Upsets Errors

Energy @Target MeV	Device No	File #	Cumulated Dose rad	Run time s	Fluence p/cm²	Minor Ref.	Minor Ramp	Major Chronic
200,2	11	001	5,820E+02	2014	1,000E+10	0	2	1
200,2	12	003	1,055E+03	1805	1,813E+10	2	3	1
149,9	12	004	2,463E+03	2009	2,000E+10	0	0	0
149,9	12	005	5,793E+03	1045	3,734E+10	0	0	0
149,9	13	006	7,040E+03	2756	1,000E+11	6	4	0
149,9	11	007	7,040E+03	2657	1,000E+11	1	3	1
300,3	14	008	9,180E+02	210	2,004E+10	2	1	0
300,3	15	009	9,173E+02	274	2,002E+10	1	1	0
300,3	13	010	9,174E+02	322	2,003E+10	0	1	0
99,6	14	011	3,771E+03	2294	4,012E+10	3	3	0
49,2	14	012	1,008E+04	5118	3,894E+10	2	0	0
49,2	15	013	5,429E+03	4304	3,385E+10	1	0	1
					Total	18	18	4

Figure 5 - CS5101A Protons Test Results



10. DEVICE PREDICTIONS FOR ENVISAT ORBIT

This section presents an analytical study to assess the impact of protons, on the performance of CS5101A for Envisat orbit.

The objective was to determine the protons induced error rates in terms of upsets.

10.1 INTRODUCTION

This section presents an analytical study to assess the impact of protons on the performance of Crystal Semiconductors CS5101A 16-bit A/D converter, for Envisat orbit.

The objective was to determine the protons induced error rates in terms of upsets.
Computations have been performed using Space Radiation software together with Hirex in-house specific routines.

Solar protons originating from large solar flares were not taken into account in this study because of their lower relative influence for the mission, and also because of the low sensitivity of the device to protons.
This particular case may be the purpose of a further analysis if required.

Next paragraphs presents the methodologies and prediction results that were computed using as input the information derived from the test results and environment calculation.

10.2 PROTONS ENVIRONMENT : CALCULATION AND ANALYSIS

Protons environment comprises two components, the first one corresponding to the trapped particles of Van Allen belts, and the other to protons emitted during solar flares (not considered in this report).

The potential contribution of trapped protons to Envisat mission has been analysed and is dicussed in this section.

Trapped protons have a significant contribution to Single Event Upsets for polar orbits, in particular when passing through the South Atlantic Anomaly (SAA) and polar horns.

In SAA region, Van Allen belts reach lower altitudes and exhibit very high protons fluxes with energetic distribution up to a few hundreds of MeV.

Differential energy spectra have been calculated for Envisat orbit, using the following hypothesis :

- NASA AP8 model,
- minimum of solar activity (corresponding to a worst case figure),
- 0, 5, 10, 20, 50, 100, and 200 mm shielding thicknesses.

The thickness of material shielding shall be understood as the radius of a solid aluminum sphere at the center of which the component is located.

The orbit parameters taken into account for computation are as follows:

-Perigee: 800 kms
-Apogee: 800 kms
-Inclination: 98.54 °

Corresponding differential protons energy spectra are given in figure 6.

TRAPPED PROTONS DIFFERENTIAL ENERGY SPECTRA FOR ENVISAT ORBIT

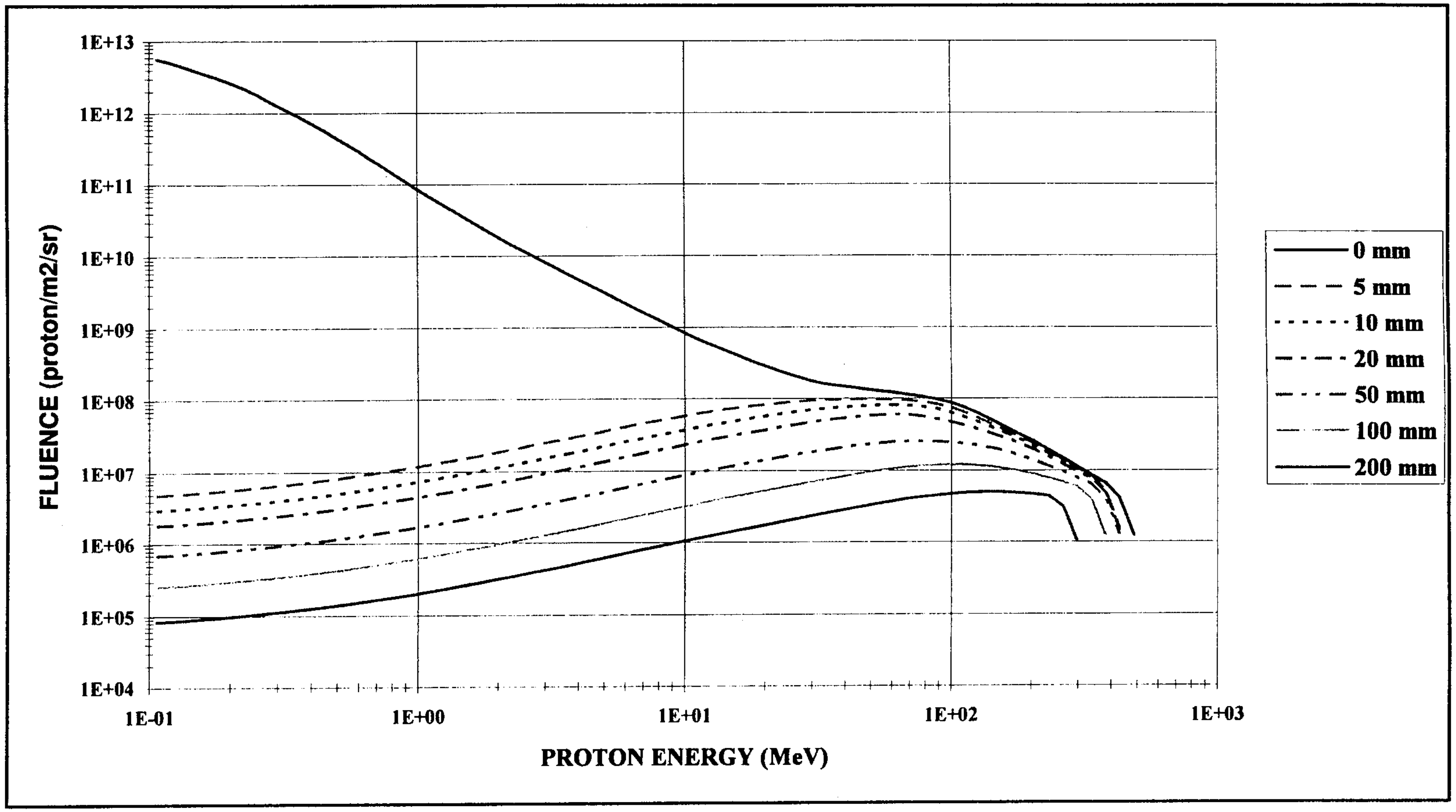


Figure 6 Differential energy spectra for trapped protons calculated at the center of aluminum solid spheres of various radii during solar minimum activity (AP8 protons model, with 1965 geomagnetic field).

10.3 IN ORBIT PREDICTION

10.3.1 METHODOLOGY AND HYPOTHESES

Upset rates can be calculated more easily with protons than with heavy ions for which calculation imposes to consider sensitive volume concept and pathlength distribution.

The basic mechanism, for protons induced upset, results from isotropic proton nuclear reactions with silicon atoms.
In this case the charge generated in a given sensitive volume is due to the energy deposited by the heavy reaction fragments of the nuclear reaction.

For practically predicting upset rates induced by protons, the present one and two parameter Bendel models constitutes the best methods [1], [2].

Both models use a semi-empirical equation that comes from the observation that much of the proton SEU cross section obtained from experimental data, as a function of protons incident energy, followed a relationship similar to that of proton nuclear reaction cross section in silicon.
The one parameter formula contains the parameter A that represents the threshold energy required to creating upsets [1].

$$\sigma = \left(\frac{24}{A}\right)^{14} \left[1 - \exp(-0.18.Y^{1/2})\right]$$

with

$$Y = \sqrt{\frac{18}{A}}.(E - A)$$

where σ is expressed in units of 10^{-12} upsets per proton / cm^2 per bit, and E in Mev.

The two parameter formula contains the parameter B in place of the constant 24 used in the previous equation [2].

The two parameter approach is supposed to give the best fit to the data.

For the purpose of our predictions for the Matra-MHS memories, we used the two parameter model to search for the best fit to the data representing the protons SEU cross section versus incident energy.

To determine A and B from experimental data [2], we used a specific routine also developed by Hirex Engineering using a least squares minimization technique.

Figures xx shows the two parameter Bendel model fitted to experimental data.

Average fits obtained, defined as the average error cross section with respect to experimental data, are in the range of xx % to yy%.

From A and B parameters, the proton induced upset rates can be simply calculated using the following equation:

$$U_p = \int \sigma_p(A,B,E).\Phi_p(E).dE$$

$F_p(E)$ being the differential protons flux determined in section 2.

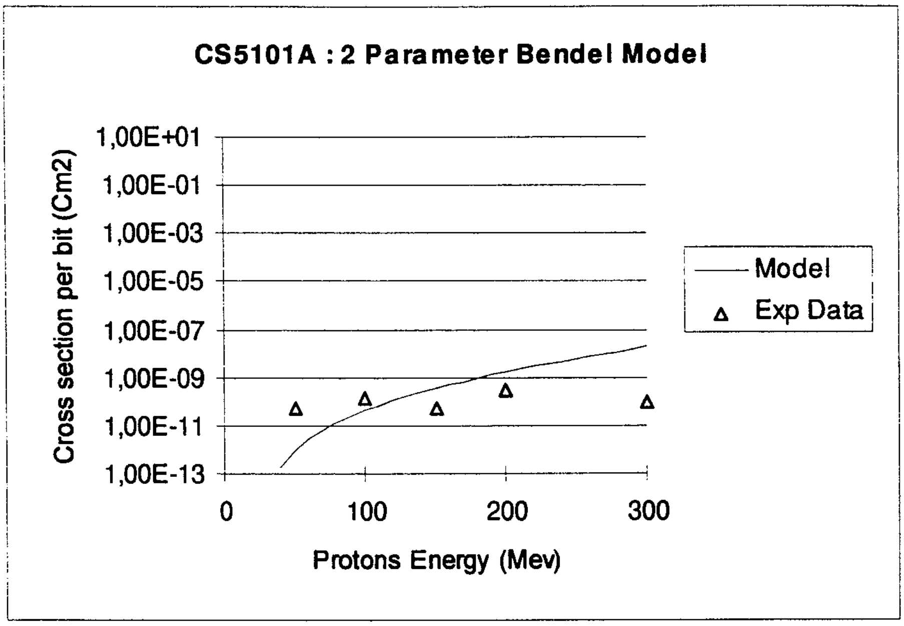


Figure 7 **Proton Upset cross section versus incident energy for CS5101A. The fit obtained with 2 parameter Bendel model is compared with experimental data.**

10.3.2 PREDICTIONS CALCULATION RESULTS AND DISCUSSION

10.3.2.1 3-2-1 PREDICTION RESULTS

Predictions calculations are presented in the figure 8, followed by a discussion of the results in the report conclusion.

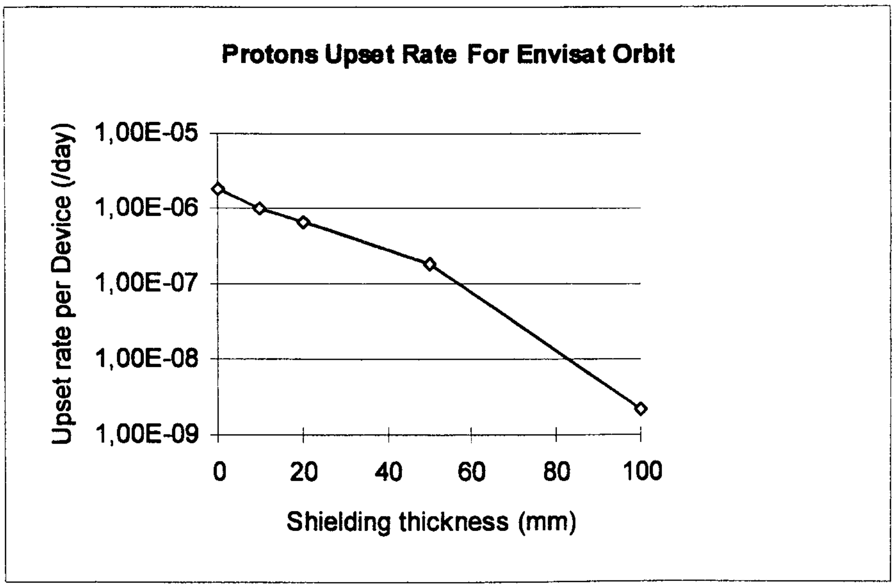


Figure 8: Proton upset rate per device is plotted for the fit conditions described in figure 7.

11. CONCLUSION

The 5 CS5101A devices have been tested with the monitoring of the 13 MSBs.

High fluences have been used due to the low number of events detected. This has led to test the 5 samples to reduce the TID cumulative effects on each sample.

The absence of results at lower protons energy does not allow for an accurate fit when using the Bendel model.

Lower energy test was not possible due to the the limits of the facility (lower flux for lower protons energy), combined with the need of much higher fluences and then, increasing TID effects.

However, the low sensitivity observed on these devices, does not call for more accurate predictions.

12. REFERENCE DOCUMENTS

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