The Embedded Local Monitor Board (ELMB) in the LHC Front-end I/O Control System

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Abstract

The Embedded Local Monitor Board is a plug-on board to be used in LHC detectors for a range of different front-end control and monitoring tasks. It is based on the CAN serial bus system and is radiation tolerant and can be used in magnetic fields. The main features of the ELMB are described and results of several radiation tests are presented.

I. INTRODUCTION

A versatile general-purpose low-cost system for the front-end control, the Local Monitor Box (LMB) was designed in 1998 and tested by ATLAS sub-detector groups in test-beam and other applications [1]. Based on this experience and to match all the needs of the ATLAS sub-detector groups a modified version, the Embedded Local Monitor Board (ELMB) was designed. The main difference as compared to the LMB is the plug-on feature and the small size (50x67 mm). It can either be directly put onto the sub-detector front-end electronics, or onto a general-purpose motherboard which adapts the I/O signals. In order to make the ELMB available for evaluation a small-scale production of 300 boards has been made.

A. Environmental Requirements

The ELMB is intended to be installed in the underground cavern of LHC detectors. As an example of such radiation environments the simulated radiation levels [2] for 10 years of operation of the ATLAS Muon MDT detectors are given below:

- Total Ionising Dose (TID): 6.4 Gy,
- Non-Ionising Energy Loss (NIEL): $3{*}10^{11}$ neutrons/cm^2 (equivalent to 1 MeV Si)
- Single Event Effect (SEE): $4.8{*}10^{10}$ hadrons/cm^2 (>20 MeV)

The magnetic field in which the Muon detectors operate is 1.5 Tesla, which makes it difficult to use DC to DC converters and other ferromagnetic components including transformers that are often used in commercial, off-the-shelf systems. These components have been avoided in the design of the ELMB. Another requirement is remote operation up to a distance of 200 m.

II. DESCRIPTION OF THE ELMB

The ELMB has an on-board CAN-interface and is in-system programmable, either via an on-board connector or via CAN. There are 18 general purpose I/O lines, 8 digital inputs and 8 digital outputs. Optionally a 16-bit ADC and multiplexing for 64 analogue inputs is provided on-board as shown in Figure 1.

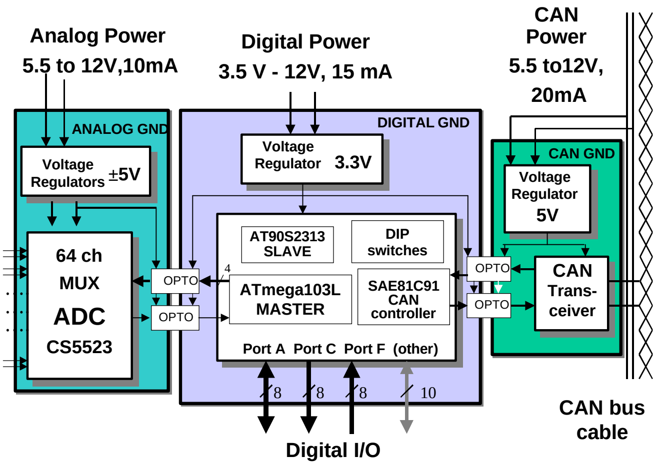


Figure 1: Simplified block diagram of the ELMB module

A. Power distribution

As seen from Figure 1 the ELMB is divided into three sections: analog, digital and CAN. They are separated with optocouplers to prevent current loops. The three parts are each equipped with a Low Dropout (LDO) 80 mA voltage regulator from Micrel (MIC5203). These regulators provide current and thermal limitations, which is a useful feature for protection against Single Event Latch-up (SEL). The analog circuits need ±5V, which is generated by a separate CMOS switched-capacitor circuit. The total analog current consumption is 10 mA. The power supply of the digital section is 3.3V, 15mA. The CAN part of the ELMB may be powered via the CAN cable and needs 20mA at 5.5V.

B. The Analog Circuits -ADC

A 16 bit differential delta-sigma ADC with 7 bit gain control (Crystal CS5523) is used and placed on the back-side of the printed circuit board. The CS5523 is a highly integrated CMOS circuit, which contains an instrumentation chopper stabilised amplifier, a digital filter, and calibration circuits. 16 CMOS analog differential multiplexers expand the number of inputs to 64. The AD680JR from ANALOG DEVICES supplies a stable voltage reference. The ADC input can handle a range between +4.5 and –4.5V. Figure 2 shows the backside of the printed circuit board with the ADC, the voltage reference and 16 multiplexer circuits.

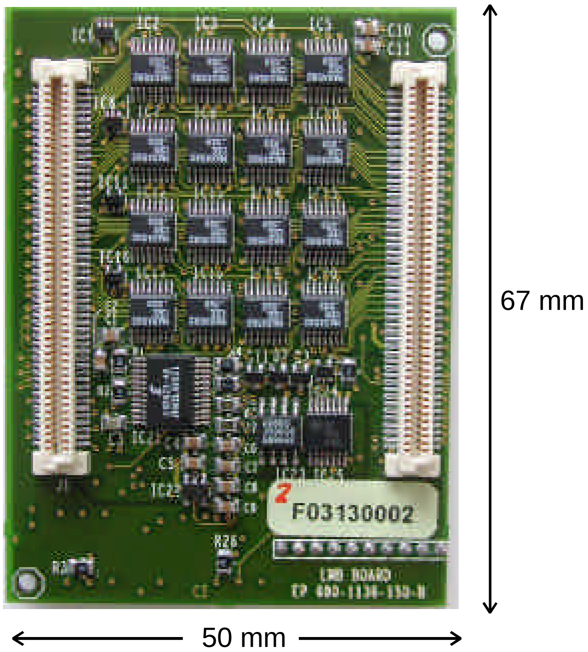


Figure 2: The backside of the ELMB printed circuit board

C. *The Digital Circuits*

The local intelligence of the ELMB is provided by 2 microcontrollers of the AVR family of 8-bit processors, manufactured by ATMEL. This family of microcontrollers is based on a RISC processor developed by Nordic VLSI and is particularly efficient in power consumption and instruction speed. The ELMB's main processor is the ATmega103L running at 4 MHz. This CMOS integrated circuit contains on-chip 128 Kbytes of flash memory, 4 Kbytes of SRAM, 4 Kbytes of EEPROM and a range of peripherals including timers/counters and general-purpose I/O pins. The main monitoring and control applications are running on this processor.

The second on-board microcontroller is a much smaller member of the same AVR family, the AT90S2313 with 2 Kbytes flash-memory, 128 bytes of SRAM and 128 bytes of EEPROM. The main purpose of this processor is to provide In-System-Programming (ISP) via CAN for the ATmega103L processor. In addition it monitors the operation of the ATmega103L and takes control of the ELMB if necessary. This feature is one of the protections against SEE. In turn the ATmega103L monitors the operation of the AT90S2313 and provides ISP for it. Figure 3 shows the front-side of the ELMB printed circuit board with the two microcontrollers and the CAN circuit.

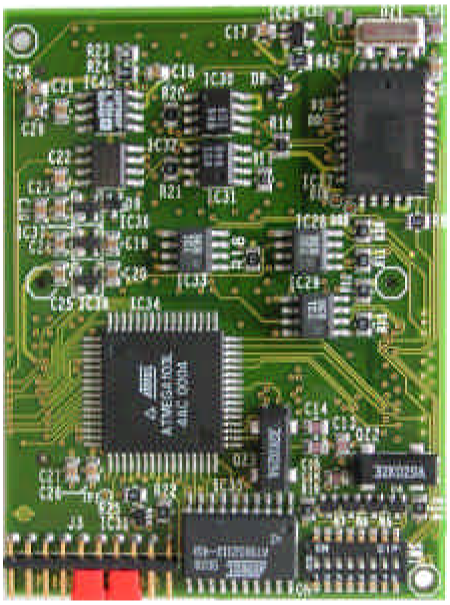


Figure 3: The front side of the ELMB

D. *CAN circuits*

CAN is one of the three CERN recommended fieldbuses [3]. It is especially suited for sensor readout and control functions in the implementation of a distributed control system because of reliability, availability of inexpensive controller chips from different suppliers, ease of use and wide acceptance by industry. The error checking mechanism of CAN is of particular interest in the LHC environment where bit errors due to SEE will occur. The CAN controller registers a node's error and evaluates it statistically in order to take appropriate measures. These may extend to disconnecting the CAN node producing too many errors. Unlike other bus systems, the CAN protocol does not use acknowledgement messages but instead signals any error that occurs.

For error detection the CAN protocol implements three mechanisms at the message level:

- Cyclic Redundancy Check (CRC)
- Message frame check
- Acknowledgement errors

The CAN protocol also implements two mechanisms for error detection at the bit level:

- Monitoring
- Bit stuffing

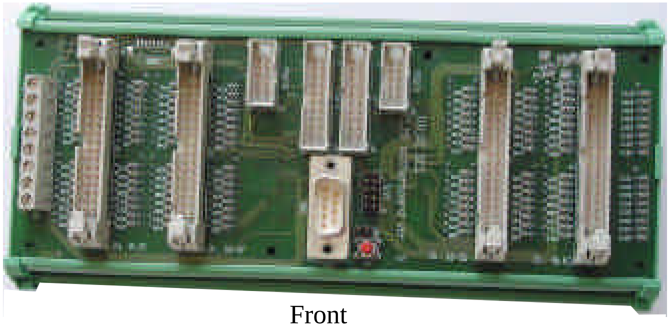
If one or more errors are discovered by at least one station using the above mechanisms, the current transmission is aborted by sending an error message. This prevents other stations accepting the faulty message and thus ensures the consistency of data throughout the network. When the transmission of an erroneous message has been aborted, the sender automatically re-attempts transmission (automatic repeat request).

The on-board CAN-controller is the Infineon SAE81C91, a so-called ‘Full-CAN controller’ with buffers for 16 messages. It is connected to the CAN bus via high-speed optocouplers to an interface circuit (Philips PCA82C250) which translates the logic levels to CAN levels. This bipolar integrated circuit has an operating temperature range of -40 to 125 °C and contains several protection features. The microcontrollers communicate with the CAN-controller via a serial interface.

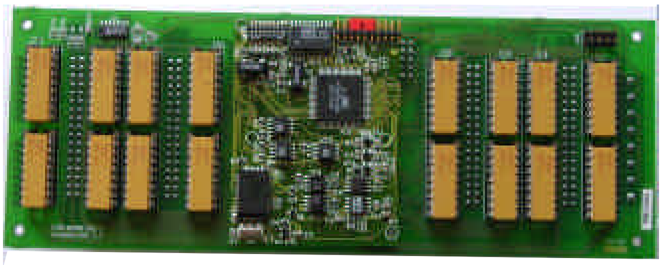
E. *Software*

CANopen [4] has been chosen as the higher layer protocol. CANopen standardises the way data is structured and is communicated. Of particular relevance for LHC applications is the network management. A master watches all the nodes to see if they are operating within their specifications. The most recent version of CANopen recommends using heartbeat messages for the supervision of the nodes. A general purpose CANopen embedded software program (ELMBio) for the ELMB Master processor has been developed [5]. 64 analog input channels, up to 16 digital inputs (PORTF and PORTA) and up to 16 digital outputs (PORTC and PORTA) are supported. The ELMBio conforms to the CANopen DS-401 Device Profile for I/O-modules and provides sufficient flexibility to make it suitable for a wide range of applications.

The ELMBio source code is available as a framework for further developments and additions by users, who want to add or extend functionality, e.g. support for specific devices [6].



Front



Back

Figure 4: The ELMB motherboard

III. ELMB MOTHERBOARD

A motherboard is available in order to evaluate the ELMB and for non-embedded applications, see Figure 4. It contains two 100-pin SMD connectors for the ELMB and sockets for adapters for the 64 channel ADC. The purpose of the adapters is to convert the input signals to levels suitable for the ADC. Adapters are available for voltage measurements and for resistive sensors in 2- and 4-wire connections. The motherboard may be mounted in DIN rail housing of the size 80x190 mm^2. On the front side are connectors for the ADC inputs, digital ports, a SPI interface, the CAN interface and power connectors.

IV. RADIATION TESTS

Several radiation tests for TID, SEE effects and NIEL have been performed.

A. *TID tests*

Three pre-selection TID tests have been made on 4 different ELMBs. Three of the ELMBs were of the first prototype series powered with 5V, while the 4th was from the 3.3V series.

1) *The Pagure test*

Two ELMBs were exposed to a Co^{60} γ-source [1 MeV] at the PAGURE facility [8]. They worked without problems until 30 Gy. At this point the power supply current started to increase by up to a factor of 10. Except for this increase, the ELMBs were basically working up to about 80 Gy when the measurements were stopped. The cause for the increase in the current was found to be the three CMOS components ATmega103L, AT90S2313 and the SAE81C91. The dose rate at this test was 77 Gy/h, which is 10^5 times higher than the ELMB is expected to receive at LHC. It was therefore decided to repeat tests at lower rates at CERN.

2) *The first GIF test*

The CERN Gamma Irradiation Facility (GIF) has a Cs^{137} γ-source [0.6 MeV]. The dose rate can be chosen in a wide range from 0.5 Gy/h down to 0.02 Gy/h. A test was done with one ELMB (given the identifier ELMB3) with a dose rate of 0.48 Gy/h [9]. The result was similar to the PAGURE test with the current increase starting at about 35 Gy. The test was stopped at 43 Gy when the current had increased by 20%. Both microcontrollers were still functional. However the in-system programming function of the master failed. The slave processor was found to be working without any faults.

3) *Accelerated ageing test*

After the radiation test the ELMB3 was tested for 12 days in a climate chamber [9]. At the same time a non-irradiated ELMB (ELMB4) was also tested for comparison. The total number of equivalent device hours reached was about 40000 h at 25 °C. Figure 5 shows how the current varied during the test. The current of the irradiated ELMB increased after each temperature increase but then decreased exponentially. The current of the non-irradiated ELMB did not show this behaviour. Both ELMBs were still operating at 85 °C, but stopped working at a temperature of 100 °C, which is outside the specifications of the components. After the test the current of both ELMBs returned to the original value. The master processor had fully recovered and could be reprogrammed.

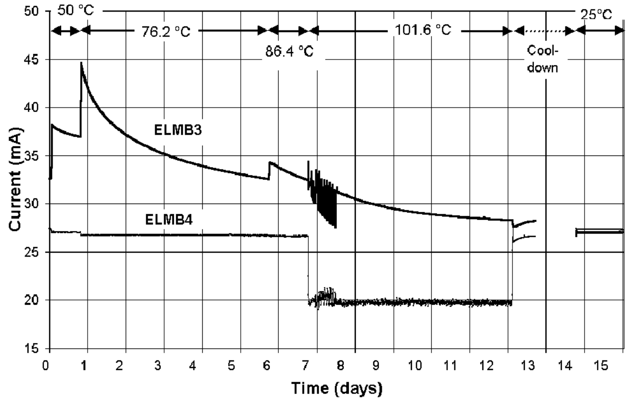


Figure 5: Current variations during the temperature test

4) *GIF test 2*

In order to test when the reprogramming function of the ELMB microcontrollers cease to work, an additional test of a 3.3V ELMB (ELMB5) was performed [10]. The irradiation was done in periods of approximately 10 hours and thereafter 14 hours break. After each step the reprogramming function was checked. This function failed after 35 Gy. At this moment a small current decrease could be observed. From then on the ELMB received a continuous dose and the current increased. Figure 6 shows how the digital currents changed for all the TID tests.

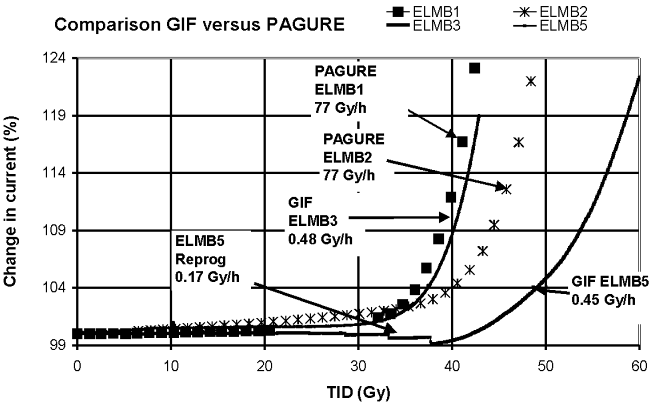


Figure 6: Comparison of the digital current for all TID tests

5) *Conclusions from the TID test of the ELMBs*

It was observed that the re-programming function of the flash memory and EEPROM in the master microcontroller ceases to work at a total received dose of around 35 Gy. Also the digital current increases substantially for a total dose of about 40 Gy. However this did not influence the operation of the ELMB up to about 80 Gy

B. SEE tests

The ELMB was irradiated with 60 MeV protons at the CYClotron of LOuvain-la-NEuve (CYCLONE) of the Université Catholique de Louvain, in Belgium [11]. The main purpose was to study SEE effects on the ELMB but also some TID measurements were made. A total fluence of $3.28*10^{11}$ protons/cm^2 was divided among 11 ELMBs. Each ELMB received an ionising dose of 39 Gy. Two types of tests were performed: a systematic test of memories and register and a functional test. They are described in detail in [11].

1) Result of the systematic memory and register tests

Special software was run in the ELMB, which in addition to the normal program also performed systematic bit tests of the different memories and registers in the ELMB. Figure 7 shows the addresses of the ATmega103L SRAM where the bit errors were located versus fluence. (The total fluence reached was $3.28*10^{11}$ protons/cm$^{2)}$.

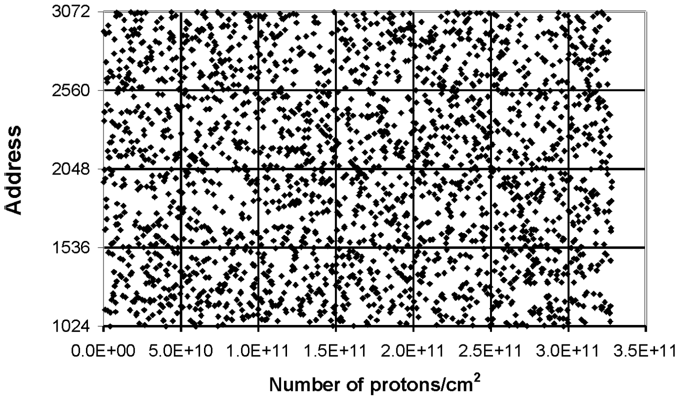


Figure 7: Addresses of the SRAM where SEE occurred versus fluence

A summary of the memory and register errors is shown in Table 1. No error was found in the flash memory or in the EEPROM. Many errors were found in the SRAM as expected. The SRAM is twice as sensitive as the registers in the CAN controller SAE81C91 and ADC CS5523.

Table 1: Results of the systematic SEU test

	No of bits Tested	**No of errors**	**Cross-section cm^2/bit**
SRAM	16384	2320	$4.3*10^{-13}$
EEPROM	28672	<1	$<1.1*10^{-16}$
FLASH	1048576	<1	$<2.9*10^{-18}$
CAN registers	320	23	$2.2*10^{-13}$
ADC registers	264	22	$2.5*10^{-13}$

2) The result of the functional SEE test

There will be in the order of 3000 ELMBs installed in ATLAS. For topological and operational reasons at most 64 ELMBs will form a CAN branch. As shown in this paper, errors due to radiation will occur. Table 2 lists the different types of errors with their symptoms, the method to recover from them and their maximally allowed rate.

Table 2: Maximum allowed SEE rates in DCS system

SEE category / Symptoms	**Error recovery**	**Maximum allowed rate**
Soft SEE / Data readout errors	Automatic recovery	1 every 10 minutes per CAN branch
Soft SEE / CAN node hangs	Software reset	1 every 24 hours per CAN node
Soft SEE / CAN branch hangs	Power cycling	1 every 24 hours per CAN branch
Hard SEE / Permanent error	Replace ELMB	1 every 2 months for 3000 ELMBs
Destructive SEE/ Damage	Power limitation	Not allowed

In total there were 29 abnormal situations detected in 131157 CAN messages recorded for $3.28*10^{11}$ protons/cm^2, These events are divided in categories according to how the normal behaviour was restored, see Table 3.

Table 3: Results of the SEE test compared with requirements

SEE category/ Recovery	**Result of the SEE test**	**Requirements**
Soft SEE / Automatic recovery	20	2604
Soft SEE / Software reset	5	1157
Soft SEE / Power cycling	4	18
Hard SEE	0	0.006

Of the SEEs, which required power cycling, one was due to an increase in the digital current and therefore believed to be a SEL. All other SEEs are soft SEE. No hard or destructive SEEs were found. All ELMBs were working perfectly after the test.

4) TID effects

The dose amounted to 39 Gy for 10 of the ELMBs and to 44.5 Gy for one of the ELMBs. The TID is estimated using a conversion factor $1.0*10^{10}$ protons/cm^2 corresponding to an ionising dose of 13 Gy for 60 MeV protons. The average fluence per ELMB was $3.0*10^{10}$ protons/cm^2. The power supply currents were measured on-line. The change measured was negligible (< 0.3%). All voltages of the LDO regulators and the ADC voltage reference were also found to be unchanged. Finally all ELMBs were checked to see if the reprogramming function of the microcontrollers was still working. They all proved to work perfectly.

C. NIEL

Tests on 10 ELMBs at the PROSPERO reactor with 1 MeV neutrons were done to test the bipolar components of the ELMB. 5 of the ELMBs were irradiated to $6*10^{11}$ n/cm^2 (equiv. 1 MeV Si) while the other 5 to $3*10^{12}$ n/cm^2 (equiv. 1 MeV Si). All 10 were found to be perfectly working after the test. Measurements on the bipolar LDO voltage regulators and the voltage references AD680JR showed that they were all within specifications.

V. CONCLUSIONS

The ELMB has proven to be a versatile general-purpose I/O device, very well matched to the needs of the LHC experiments. All ATLAS subdetectors have decided to use it on a large scale - the biggest system comprising 1200 ELMBs. CAN is an excellent choice for the read-out due to its robustness and error handling facilities. It has also been shown that by using COTS a certain level of radiation tolerance can be achieved. For example the requirements for the ATLAS Muon detector MDT are fulfilled concerning SEE and NIEL. The required TID figures including a safety factor of 7 varies from 9.3 Gy to 44.7 Gy for the different MDT chambers. For more than 97% of them the requirements are fully satisfied. More investigations and possibly some special measures may be required to use the ELMB for the rest of the chambers.

VI. ACKNOWLEDGEMENTS

We would like to thank M.Dentan for helping us with the definition and execution of the radiation tests. We are grateful to the EP-ESS group for collaborating in the production of the ELMB and to the EP division for the support as a Common Project.

VII. REFERENCES

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