Neutron Radiation Tolerance Tests of Optical and Opto-electronic Components for the CMS Muon Barrel Alignment

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Abstract

Neutron irradiation tests were performed with broad spectrum p(18MeV)+Be neutrons (E_n<20MeV, <E_n>=3.5MeV) to study the neutron induced alterations of COTS (Commercially available Off The Shelf) optical and opto-electronic components (LED light source, LED driver, microcontroller, video camera, optical lens) of the CMS Muon Barrel Alignment system. Results of the tests are presented in this paper.

I. INTRODUCTION

Performance of the CMS detector [1] of the Large Hadron Collider (LHC) is affected by the position and orientation of the individual detectors. Therefore, the CMS detector has an alignment system that consists of:

a) The *internal alignment of the inner tracker,* which measures any deformation of the tracker.
b) The *link system* , which transfers the position of the tracker to linking points located between the barrel and the end-cap muon regions.
c) The *barrel and end-cap internal alignments,* which measure the positions of the muon detectors with respect to the linking points.

In the case of the barrel muon chambers of the muon detecting system of the CMS [2], the positions of the sensing wires have to be known with a precision of 75 micrometers. In order to achieve the requested accuracy, rigid mechanical structures called MABs (Module for Alignment of the Barrel) will be fixed on the iron absorbers of the muon detectors. A sophisticated Barrel Alignment Monitoring (BAM) system (Figure 1) will also be employed. It will operate on the basis of the information that will be provided by the Barrel Alignment Control (BAC) system. The precision of the internal monitoring system should not exceed 55 microns.

This BAC system will consist of LED light-sources (~10.000 pcs.), the related electronics (~1.000 pcs) with LED driver and controller components and video cameras (~400pcs) equipped with video-sensors and optical lenses. Video cameras will be mounted on the MABs and they will monitor the positions of the LED light-sources fixed on the barrel muon chambers.

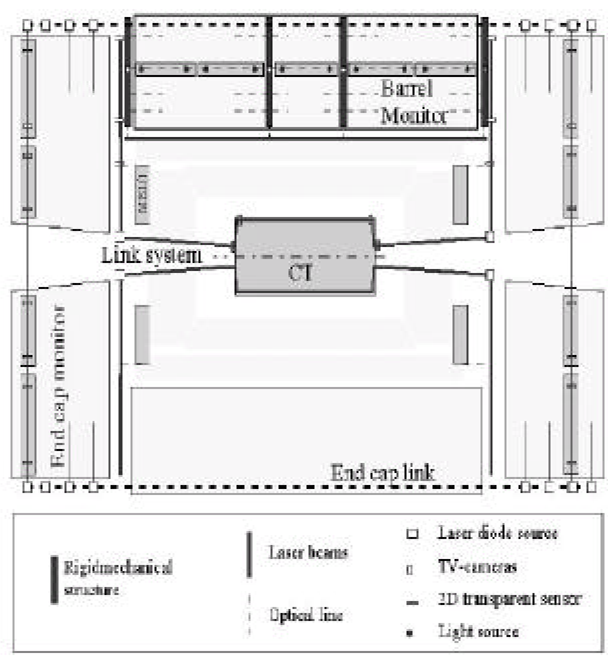

Figure 1. The Barrel Alignment Monitoring scheme.

The integration and supervision of the components will be performed by the special segmented DAQ system based on PC104 Board-Computers (~40 pcs). Modules of the fast and slow communication network are also included in the system. The whole control and monitoring electronics is a subsystem of the CMS Alignment electronics.

The optical and opto-electronic components will have to work in a radiation environment, where the highest expected flux of the neutron component is about 1.0E+03 n/cm2/sec, and the estimated time of operation is 5.0E+10 sec.

The total expected neutron fluence is 2.6E+12 n/cm2 and 8.0E+13 n/cm2 for the Barrel Muon and ME1/1 chambers, respectively [1]. Radiation damage induced by neutrons can alter electrical and optical characteristics of the components and thus the accuracy of the whole BAM system.

Our present paper addresses some key issues for the cost effective use of COTS electronic components in radiation environments that enable CMS Alignment system designers to manage risks and ensure final success [3,4].

II. EXPERIMENTAL TECHNIQUES

A. Samples tested

LED light source

Low current high intensity point-like LED light sources emitting at 660 nm were selected for construction of lighting panels of BAM system, type: FH1011, Stanley Electric Co. Ltd [5].

LED driver

The A6775 circuit is intended to use for LED-display applications [6]. Each BiCMOS device includes an 8-bit CMOS shift register, accompanying data latches, and eight NPN constant-current drivers. The serial CMOS shift register and latches allow direct interfacing with microprocessor-system. CMOS serial data output permits cascade connections in applications requiring additional drive lines. The LED drive current (max. 90mA) is determined by user's selection of a single resistor.

Microcontroller

The PIC16F84 is a high-performance, low cost, CMOS, fully static 8-bit microcontroller [7] with 1kx14 EEPROM program memory and 64-byte EEPROM data memory. The high performance of the PIC16F84 can be attributed to number of architectural features commonly found in RISC microprocessors. The chip uses a Harvard architecture, in which, program and data are accessed from separate memories. This improves bandwidth over traditional von Neuman architecture where program and data are fetched simultaneously. Separating program and data memory further allows instructions to be sized differently than 8-bit wide data word. In PIC16F84, op-codes are 14-bit wide making it possible to have all single word instructions. A 14-bit wide program memory access bus fetches a 14-bit instruction in a single cycle. A two-stage pipeline overlaps fetch and execution of instructions. Consequently, all instructions execute in a single cycle except for program branches. The PIC 16F84 has four interrupt sources and an eight-level hardware stack. The peripherals include an 8-bit timer/counter with an 8-bit pre-scaler, 13 bi-directional I/O pins and a separate watchdog timer (WDT). The watchdog timer is realised as a free running on-chip RC oscillator that does not require any external components. That means that the WDT will run, even if the clock on the oscillator pins of the device has been stopped. A WDT timeout generates a device RESET condition. The high current drive of I/O pins help reduce external drivers and therefore, system cost.

Video camera

The VM5402 is a complete video camera [8] based on the highly integrated VV5402 monochrome CMOS sensor chip [9]. The module is suitable for applications requiring a composite video signal with minimum external circuitry. The camera incorporates a 388x295 (12micron x 12micron) pixel image sensor and all necessary support circuits to generate fully formatted composite video signal into a 75 Ohm load. Automatic controls of exposure, gain and black level allow use of a single fixed-aperture lens over a wide range of operating conditions. Automatic exposure control is achieved by varying pixel current integration time according to the average light level on the sensor. This integration time can vary from one pixel clock period to one frame period. Pixels above a threshold white level are counted every frame, and the number at the end of the frame defines the image exposure. If the image is other than correctly exposed, a new value for integration time is calculated and applied for the next frame.

Optical lens

The lenses were plano-convex single lenses made of BK7 glass without coating. Their nominal focal length was 30.7mm and their diameter was 10 mm.

B. Irradiation circumstances

Neutron irradiations were done at the neutron irradiation facility [10] at the MGC-20E cyclotron at ATOMKI, Debrecen with p(18MeV)+Be reaction. Neutrons with a broad spectrum (E_n<20MeV, <E_n>=3.5MeV) were produced by bombarding a 3mm thick target by protons of 18 MeV. Neutrons emitted by the neutron source were inherently associated by gamma photons. The additional gamma doses were measured by the twin ionisation chamber method [11]. The gamma dose/neutron flux ratio depended on the irradiation circumstances. Typically it was in the range of (3-5)E-10 rad cm2s/neutron. All irradiations and measurements were performed at room temperature.

C. Electronic test set-up and measurement

A few different test set-ups were designed for on-line testing of the major functionality of the circuits of the BAC system under irradiation.

Three different modes of operation were investigated: a) voltage ON permanently, b) voltage OFF permanently,

c) voltage ON/OFF alternating in ratio to 1/19 for testing of the *LED light-sources*. The LED power rails were monitored using digital multimeters equipped with serial communication interface that allows automatic measurement of the LED current. The nominal current were checked post irradiation if any total dose degradation has occurred. Before and after irradiation the optical properties (light yield, intensity distribution, wavelength of the emitted light) of the diodes were measured and evaluated with a commercial PC based image analysing system.

In order to determine the radiation tolerance of the chip itself the *LED driver* circuit was also investigated separately from the PIC microcontroller. For this purpose the special set-up was constructed consisting of a Power-PC with serial RS-232/I^{2}C/RS-232 bus converter and interface for measuring the current consumption of the circuit automatically. The current source outputs of the LED driver were terminated using radiation tolerant resistors as replacing of the LEDs. Using special ON/OFF codes for up dating the content of the serial 8-bit register inside the chip resulted in a direct possibility to detect bit errors by measuring the total current only.

The most important electronic component of the Barrel Alignment Control system is the *PIC16F84 microcontroller* that is an advanced highly scaled sensitive device. As it will work in a radiation environment, its radiation tolerance is one of the most crucial questions. The errors and Single Event Upsets (SEU) in these kind of systems may not be observed, may cause data corruption, or may alter program flow depending on the location of the upset [12]. The consequence of these upsets is dependent on the criticality of the function performed by the system.

The SEU characterisation of the microcontroller was performed by using a special test set-up. The test system based on the PC equipped with the whole necessary measuring and communication devices was placed outside the irradiation area in 30-meter distance from the devices under test. The special test code developed and run on the PC was able to communicate with the controller trough the I^{2}C bus regularly sending special commands and data associated with it. After a fixed irradiation time (1-10 minutes) the content of the registers of the PIC was read back and compared to the initial values. If the register content was changed by the radiation, i.e. the expected and received values differed, the errors with time stamps were registered in a report file before the register was filled again in the next irradiation cycle.

The watchdog timer as one of the useful functions of the microcontroller was intensively used during the irradiation as basic indicator of the system general failure. The supply current of the PIC was automatically measured and compared to the reference value. In case of higher current consumption, then the default value, i.e. due to the Total Ionising Dose (TID) effect the test set-up was able to interrupt the measurement by switching off the voltage.

The compact monochrome *VM5402 video camera* together with the related circuits was tested on-line during the full irradiation period. An automatic radiation damage monitoring system was developed and used for characterisation of the radiation tolerant ability of the device. The system was based on a video-monitor and a videotape recorder in order to record the video signal for off-line coding and evaluation. In direct connection with the monitoring system a PC equipped with a Frame Grabber card was used for capturing and digitising of the video frames periodically in every 1 minute. The actual current consumption of the camera was measured to avoid the TID threshold of the device. During the camera irradiation measurements different modes of operation were investigated similarly to the LED's tests.

D. *Optical set-up and measurement*

The focal length (and thus indirectly the refractive index) and spectral transmission characteristics of the lenses was measured before and after irradiation. A He-Ne laser was used for focal length measurements. A high-pressure xenon arc lamp was employed as light source for the spectral transmission measurements. A calibrated Si-UV detector was used to measure spectra.

III. RESULTS AND DISCUSSIONS

A. *Electronic measurements*

Low current high intensity point-like *LED light sources* emitting at 660 nm were irradiated up to 2.6E+12 n/cm2. Three modes of operation were studied: a) voltage ON permanently, b) voltage OFF permanently and c) voltage ON for 1 sec and OFF for 19 sec. For all of these modes of operation, the light yield decreased almost linearly as a function of the neutron fluence and approximately 50 % decrease was observed at the end of the irradiation. No other change in the electrical and spectral characteristics was measurable (Figure 2).

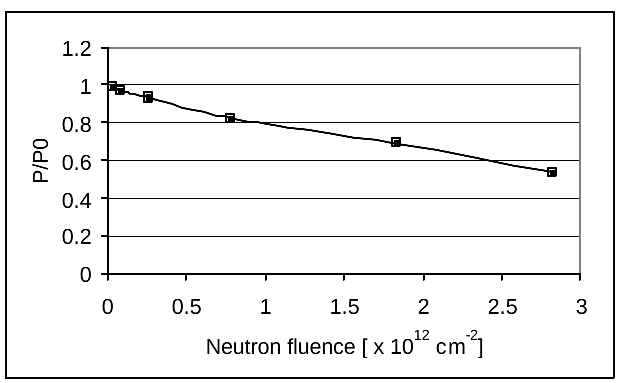

Figure 2. Light yield of the LED vs. neutron fluence

LED current driver and controller electronics with Microchip *PIC16F84 microcontroller* were irradiated up to 8.0E+13 n/cm2. Some 20 % loss of the output currents of the LED controllers was observed at the end of the irradiation (Figure 3).

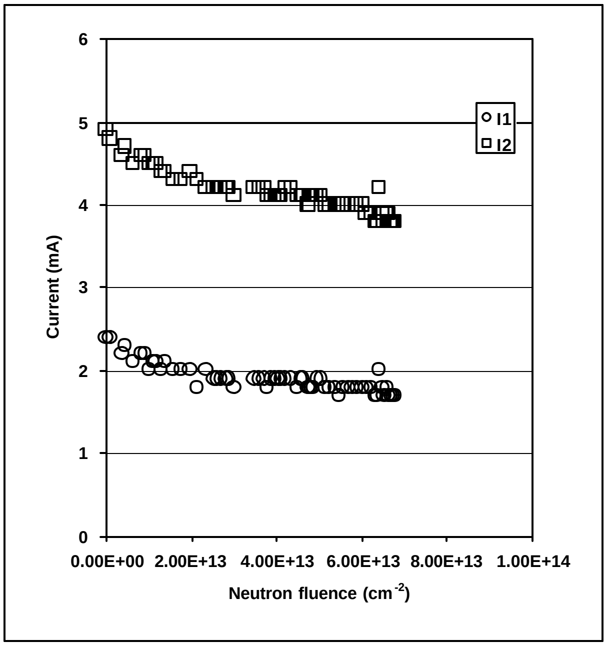

Figure 3. Current of the LED driver vs. neutron fluence

The degradation of the current drivers was negligible below 1.0E+11 n/cm2 (the expected fluence at the position of operation of the device). Two microcontrollers were studied. Both became damaged only after delivering ~ 2.0E+13 n/cm2 neutron fluence to them as the dramatically increased current consumption of the electronics indicated (Figure 4).

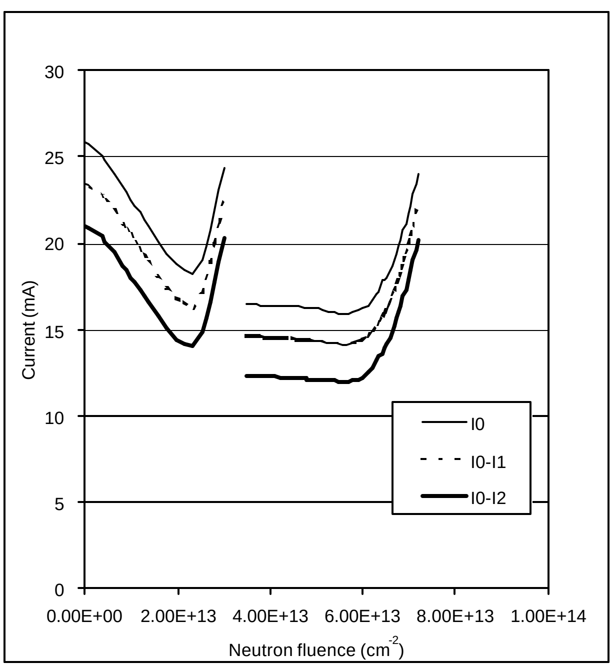

Figure 4. Current consumption of LED driver & controller electronics vs. neutron fluence

VM5402 video cameras with VV5402 CMOS sensor device were irradiated with a fluence up to 2.8E+12 n/cm2. The radiation damage of the sensor resulted in the altered nearly Gaussian distribution of the light sensitivity of the individual pixels in all modes of operation. The mean values decreased while the sigma values increased in all three modes (a) voltage on permanently, b) voltage off permanently and c) voltage on for 1 sec. and off for 19 sec (see Table 1).

Table 1. Homogenity of the video sensor (Parameters of the nearly Gaussian distribution of the sensitivity of the individual pixels)

	Before irradiation	After irradiation	Before/After irradiation
	Mean / Sigma	Mean / Sigma	Mean / Mean
DC permanently ON	230.18 / 1.20	153.22 / 2.58	66.6 %
DC periodically ON (5 % in total)	211.85 / 1.31	158.45 / 2.06	74.8 %
DC permanently OFF	238.09 / 0.81	210.39 / 1.51	88.4 %

The observed nonlinearity of the output signal vs. light intensity was not radiation-dependent. Apart from the general sensitivity loss, the spectral sensitivity of the sensor did not change (Figure 5).

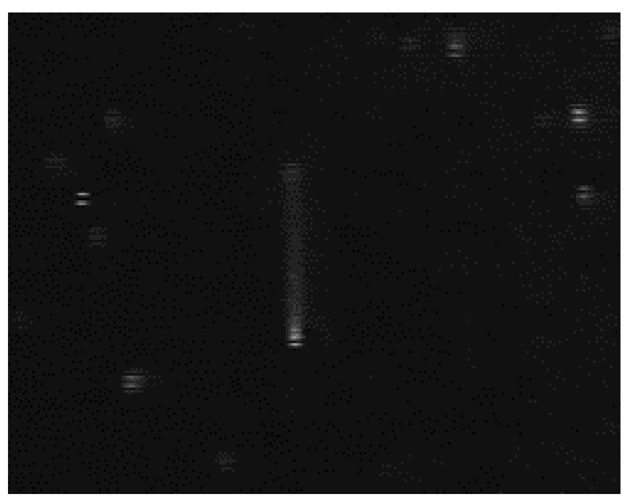

Figure 5. Typical picture of the video camera at the beginning of the neutron test. Tracks of recoils could be observed frequently

B. Optical measurements

Plano-convex single *optical lenses* were irradiated up to 8.0E+13 n/cm2. They were made of BK7 glass without coating and their diameter was 10 mm. No measurable change of the spectral transmission and the refraction (focal length) was observed.

IV. CONCLUSIONS

Neutron radiation tolerance of COTS optical and opto-electronic components to be used in the CMS Muon Barrel Alignment system was studied with broad spectrum p(18MeV)+Be neutrons (E_n<20MeV, <E_n>=3.5MeV). The observed magnitudes of the alterations of the optical and electric characteristics of the tested components indicate that they can operate and function in the expected radiation environment of their operational position in the Barrel Muon Alignment System after an exposure of the relevant expected neutron flunce.

V. ACKNOWLEDGEMENTS

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