Available on CMS information server

**CMS NOTE 2003/008**

The Compact Muon Solenoid Experiment

**CMS Note**

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

**June 9, 2003**

# Proton irradiation of analogue opto-hybrid circuits for the CMS tracker

M.T. Brunetti[a], B. Checcucci[a], V. Postolache[a], D. Ricci[a]
T. Bauer[b], M. Friedl[b] and M. Pernicka[b]

[a]*INFN and University of Perugia, Via A. Pascoli 1, I-06123 Perugia*

[b]*HEPHY, Nikolsdorfergasse 18, A-1050 Wien*

**Abstract**

Four analogue opto-hybrid circuits to be used in the front-end electronics of the CMS (Compact Muon Solenoid) tracker were irradiated with 26 MeV protons to fluences of $0.5 \cdot 10^{14}$ p/cm$^2$ and $0.8 \cdot 10^{14}$ p/cm$^2$ in the secondary beam of the cyclotron at the Forschungszentrum (FZK) in Karlsruhe (Germany). The measurements done during the irradiation are reported and discussed and the circuit performance, tested before and after the irradiation, is compared.

# 1 Introduction

The CMS silicon tracker [1], with its capability of collecting a huge amount of data from high energy proton-proton interactions in the LHC tunnel, is an outstanding example of the frontiers achieved in the fields of physics and technology.

About 10 million channels will be involved in the trajectory reconstruction and this has led to the development of front-end electronics which are fast, compact and very resistant to the harsh radiation environment. The calculated energy integrated fluence for fast hadrons in 10 years is $1.6 \cdot 10^{14}$ $cm^{-2}$ in the inner tracker layer and $0.35 \cdot 10^{14}$ $cm^{-2}$ in the most outer layer [1].

Optical links [2,3], typically 60 m long, will allow the transfer of data at a frequency of 40 MHz from the detector to the control room, where analogue pulses are digitised and processed at the Front-End Driver (FED) [4]. Two types of optical links will be used in the CMS tracker, a bi-directional digital control link and an analogue readout link.

The conversion of analogue electrical signals into the corresponding optical ones is done by means of an analogue opto-hybrid (AOH) circuit. Several versions of it were developed and tested by the CMS collaboration in Perugia, Vienna and at CERN [5,6]. The specific geometric requirements for the various parts of the tracker, i.e. inner barrel and inner disks (TIB/TID), outer barrel (TOB) and end caps (TEC) led to three layouts of the AOH circuit. The total number of AOHs to be built and tested for the CMS tracker amounts to about 17000. Figure 1 shows the scheme of the analogue part of the optical link. The pulses induced by charged particles passing through the silicon detector are sampled and multiplexed by APV chips [7] and MUX. The resulting differential input voltage is converted by the AOH into an analogue optical signal and is transmitted via optical fibres to the back-end electronics. Each fibre will carry the multiplexed signals of 256 microstrips.

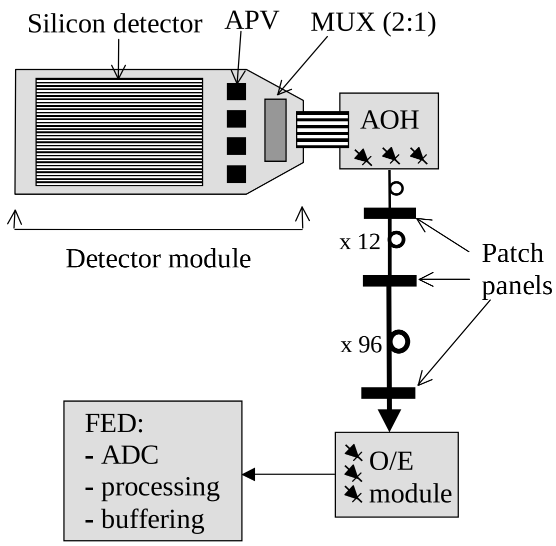



Figure 1: Scheme of the analogue part of the CMS tracker optical readout link.

Patch panels group together the fibres into optical cables that arrive at the back end electronics in the control room. Here optical signals are re-converted into electrical and are processed.

# 2 The analogue opto-hybrid circuit

The analogue opto-hybrid circuit for the CMS silicon tracker consists of a FR4 (vetronite) substrate with dimensions of 30x22x0.5 $mm^2$ for the TIB/TID and slightly larger, 30x23x0.5 $mm^2$, for the TOB and TEC.

All three AOH types are equipped with one linear laser driver (LLD) chip [8] and 2 or 3 laser diodes. The LLD is programmable via an $I^2C$ interface and can be set to bias the laser diodes in their linear operational region. Four increasing gains (5, 7.5, 10 and 12.5 mS) of the differential input signals are pre-settable through the LLD in order to compensate for threshold variations due to radiation damage.

The laser diodes are commercially available InGaAsP edge-emitting coupled to single mode optical fibers operating at a wavelength of 1310 nm. They are glued to the substrate with a thermally conductive resin which is resistant to radiation and are ultrasonically bonded. A version of the TOB AOH with laser diodes soldered to the substrate has also been developed, but will not be used in the final system.

Figure 2 shows the pictures of the AOHs irradiated in Karlsruhe, where (a) shows the TIB/TID AOH front and back side, (b) the TOB AOH with laser diodes bonded on the substrate and (c) the TOB AOH with soldered laser diodes.

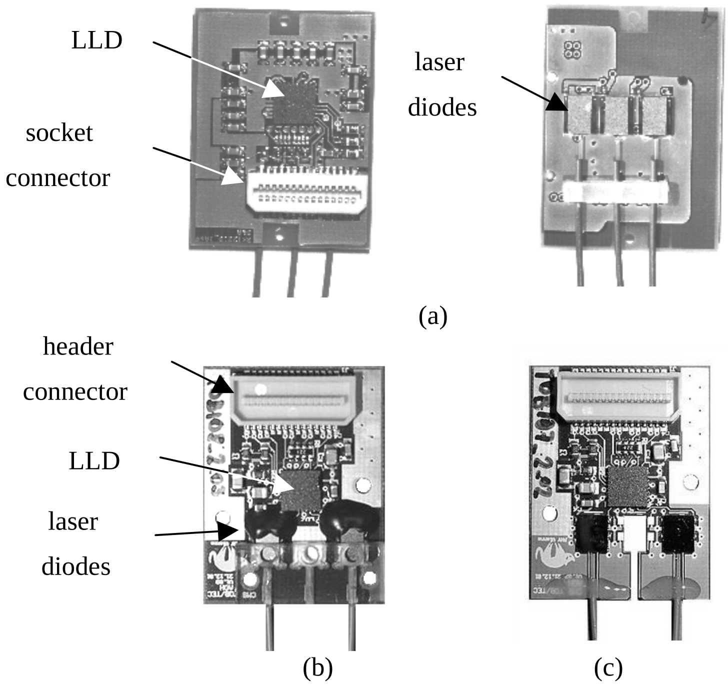



Figure 2. (a) Front side and back side of the TIB/TID analogue opto-hybrid. (b) TOB analogue opto-hybrid in the bonded version. (c) TOB analogue opto-hybrid in the soldered version.

The link to the detector module is done through a 30-pin NAIS connector, socket type for the TIB/TID and TEC and header type for the TOB. Due to mechanical constraints, in the TIB/TID AOH the LLD and the connector are on the opposite side of the substrate with respect to the laser diodes, while they are on the same side for the TOB and TEC versions. In order to protect the bonds during assembly and handling, wires are hard covered with a plastic (ABS) stamp (not present in fig. 2).

# 3 Proton irradiation

The irradiation of the analogue opto-hybrid is the final step in the qualification of this circuit for resistance to radiation damage.

Previous qualification was dedicated only to components of the AOH, i.e. laser diodes, fibres and connectors [9,10], LLD [8], substrate, passive electrical components and glues [11]. The results obtained already gave a good level of confidence on the AOH radiation hardness. Nevertheless, the response to radiation had also to be proven once assembled with all its parts.

Four AOHs, two TIB/TID and two TOB, were irradiated in a secondary beam of the KIZ isochrone cyclotron at the Forschungzentrum in Karlsruhe. The irradiation source is a proton beam of 26 MeV with a current adjustable from 400 nA to 2 μA. Figure 3 shows the beam area.

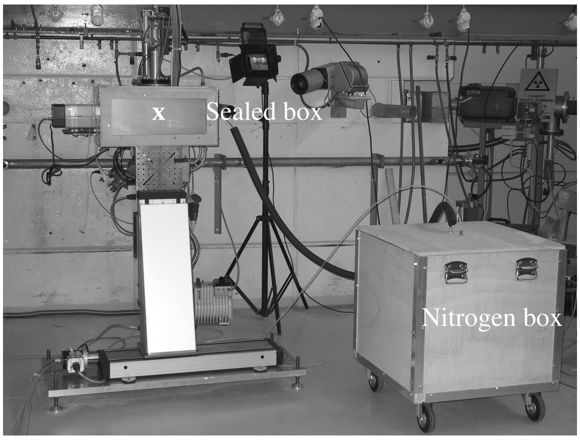



Figure 3. Picture of the cyclotron beam area with the scanning system facility.

A scanning system, placed on a rail, allows uniform irradiation of the target. The circuits are contained inside the sealed box placed in front of the beam (represented by the white X in fig. 3). The box to the right contains the nitrogen used to cool the target.

The electrical setup used in the AOH's irradiation was built to drive the AOH circuit without the detector module, like in the final readout chain shown in fig. 1. It is represented by the scheme in figure 4.

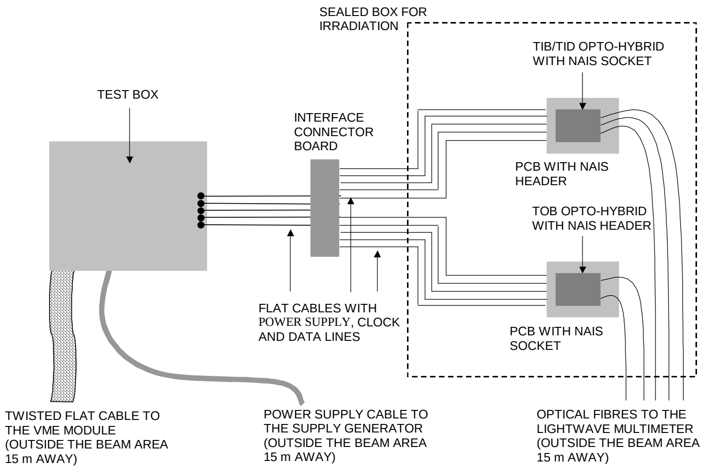



Figure 4. Scheme of the setup in the cyclotron beam area used to irradiate the 4 AOHs.

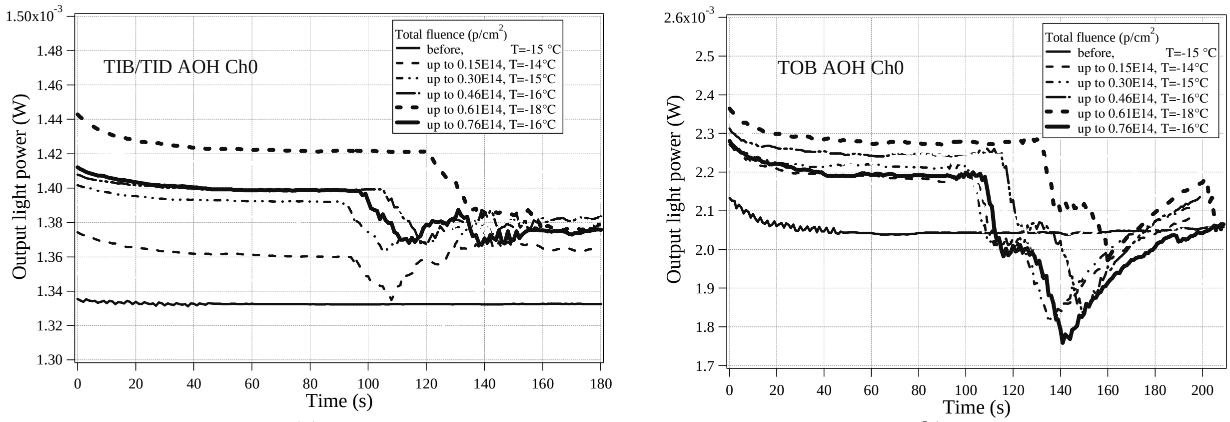
The AOHs are plugged onto two PCBs inside the sealed box, represented by the dotted rectangle in the right of the figure. They are powered and biased through the five line flat cables ($V_{DD}$, $V_{SS}$, $V_{125}$, clock and data) arriving from the front-end electronics (gray test box on the left). An interface connector board (centre of the figure) splits the signals from the test box to feed both AOHs under test. The optical fibres from the AOHs run outside the beam area to an optical power-meter (Agilent 8163A lightwave multimeter). The twisted flat cable and the power supply cable go, respectively, to a VME module and power supply generator located in the control room.

Two irradiation runs were done, with 2 AOHs at each time. Several beam stops were requested during the test, in order to monitor the rate of degradation after each irradiation step. In the first irradiation run the beam current was initially set to 400 nA and then rose up to 1 μA after 10 steps, reaching a total fluence of $0.54 \cdot 10^{14}$ p/cm$^2$. The second irradiation was performed in 10 steps, each about 1 min long, with a beam current of 1 μA and a final fluence of $0.76 \cdot 10^{14}$ p/cm$^2$. Both fluences are calculated with the beam current and are affected by a systematic error of 15%. The temperature inside the sealed box was measured by a probe placed near the AOHs and varied between –8 and –2 °C during the first irradiation run and between –18 and –14 °C during the second. All the results reported in this paper refer to the two AOHs (one TIB/TID and the soldered TOB) irradiated at higher fluence.

# 4 Monitoring during the irradiation

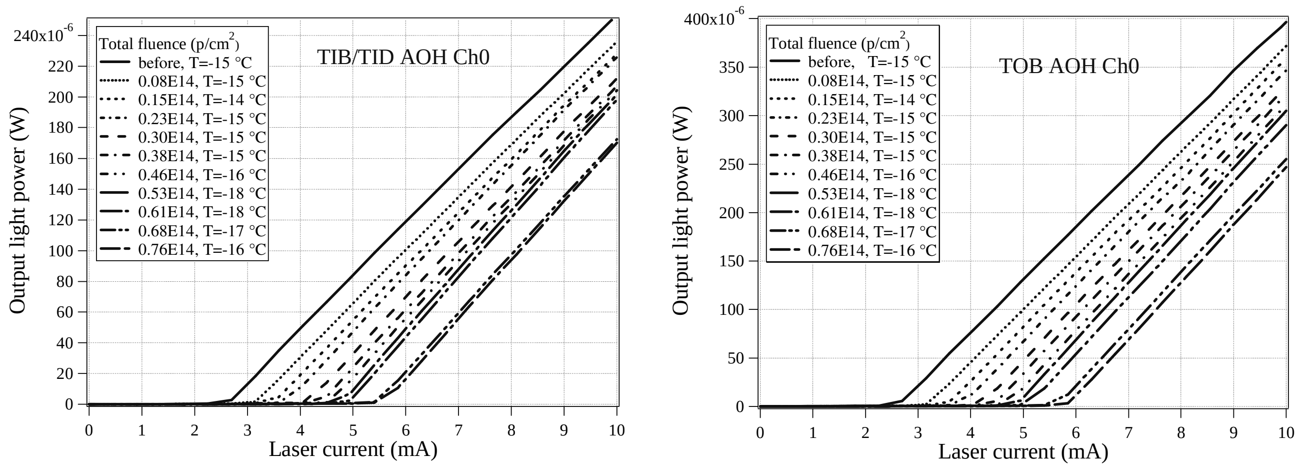
The signals carried from two optical fibres (one for each AOH) were measured during the irradiation test by the Agilent 8163A lightwave multimeter.

The measurement of the output light power as a function of time is shown in figures 5a and 5b for some increasing steps of the irradiation. The temperature inside the cooled box is reported together with the increasing fluence value. Before the beam was switched on, the laser diode was biased with a current of 45 mA, well above its threshold current that is usually around 5 mA. The initial decrease of the output light power in figs. 5a and 5b is related to the self-heating of the laser diode. Once the output power is settled, after about 60 s, the AOH is ready to be irradiated. When the beam crosses the laser diode under test, the emitted power suddenly decreases until the beam stop. A partial recovery of the initial light power was observed after some tens of second. The maximum variation of the initial output light power during the irradiation amounts to about 100 μW for the TIB/TID AOH and about 200 μW for the TOB AOH. The relationship between this variation and the irradiation is not so evident, since there is no clear correlation in these results between the expected decrease in laser diode efficiency with increasing fluence. This is instead more evident in the second type of monitoring described below.




(a) (b)

Figure 5. Output light power during the irradiation as a function of time for the TIB/TID (a) and TOB (b) AOH. The temperature measured by the probe inside the sealed box is also reported.




(a) (b)

Figure 6. Output light power as a function of bias current after each step of irradiation for the TIB/TID (a) and TOB (b) AOH.

The measurement of the output light power as a function of the bias current of the same two laser diodes (channel 0 of each AOH) was done soon after each irradiation step and is shown in figure 6. The diodes were biased with an increasing current from 0 to 54 mA in steps of 0.45 mA, that corresponds to one unit of the LLD register. In particular, the data in fig. 6 were plotted in the range 0-10 mA in order to show the laser threshold shift of about 3 mA caused by the irradiation. The temperature inside the cooled box was measured by a local probe, placed near the AOHs, and is reported together with the increasing fluence value. The dependence of the laser threshold on the temperature for non irradiated AOHs was measured in the range –15 °C to 25 °C. According to these measurements, the temperature variation reported in fig. 6 contributes to less than 10% of the total current shift.

# 5 Characterization before and after the irradiation

The monitoring of the AOH's output light during the irradiation is useful to check the immediate effect of the irradiation in the circuit behaviour. More specific tests were performed after 3 months, when the activity of the irradiated AOHs allowed a safe handling. These are the measurement, at room temperature (between 25°C and 28 °C) of some static and dynamic electrical parameters, i.e. gain, integral linearity deviation, RMS noise, bandwidth and crosstalk. The setup scheme for the AOH characterization before and after the irradiation is shown in figure 7.

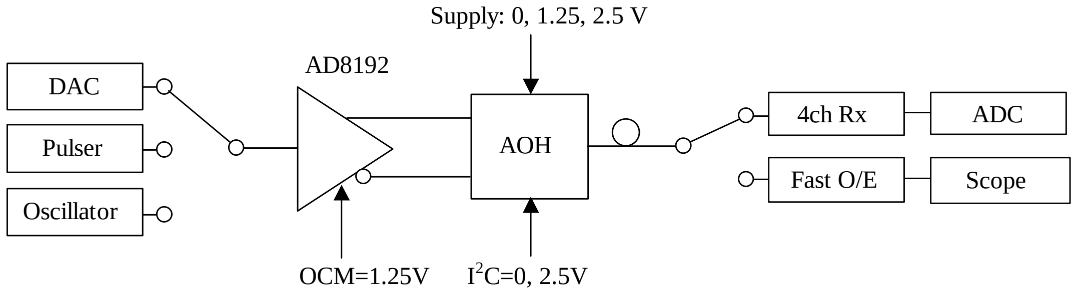



Figure 7. Scheme of the setup used for the AOH's electrical characterization before and after the irradiation.

The AOHs are biased slightly above the laser diode threshold, in their linear operational range.

The gain is the slope of the linear fit of the output voltage as a function of the input voltage in the range -300÷300 mV. The input pulse is generated by the DAC and is converted into a differential signal by the Analog Devices AD8192 amplifier. The optical output signal is transferred through the optical fibres to a 4-channel receiver module where it is converted back to an electrical output and sent to the ADC. Table I states the gain values measured on channels 0 and 1 of the TIB/TID AOH (a), and channels 0 and 2 of the TOB AOH (b), before (upper value) and after (lower value) the irradiation. The measurements show a general decrease of the gain, of 14% on average (with a spread between 0 and 30%) due to the radiation damage, which causes a lack of efficiency in laser diodes. The four columns correspond to the four LLD pre-settable gains (5, 7.5, 10 and 12.5 mS).

The integral linearity deviation (or integral non linearity, INL) is also calculated by the linear fit of the output voltage of the optical link as a function of the differential input voltage in the interval -300÷300 mV (operational voltage range). The measurements before (a) and after (b) the irradiation are reported in figure 8 for the TIB/TID and TOB AOHs for a LLD gain setting of 5 mS. The horizontal solid lines in fig. 8(a) and 8(b) correspond to the maximum value of 1.5% for INL in the operational voltage range, as requested by the CMS tracker optical link specifications [12]. Both channels of the two AOHs satisfy this constraint, before and after the irradiation.

The output voltage RMS noise is measured by a high bandwidth ADC for differential input voltage levels varying from –300 and 300 mV. The results are reported in figure 9 before (a) and after (b) the irradiation. Some increase in the noise after the irradiation was observed in all channels except for channel 2 of the TOB AOH, where even some decrease is present. The horizontal solid lines are again the limits for the average noise allowed by the specifications for the CMS tracker optical link [12].

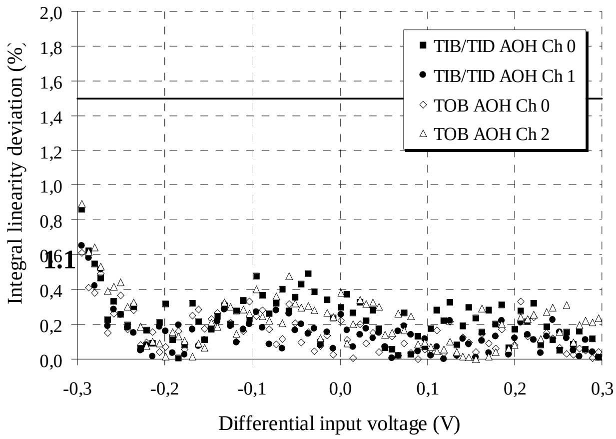
Table I: Gain values measured on the two channels of each AOH before (upper) and after (lower) the irradiation at the fluence of $0.76 \cdot 10^{14}$ p/cm$^2$.

TIB/TID AOH

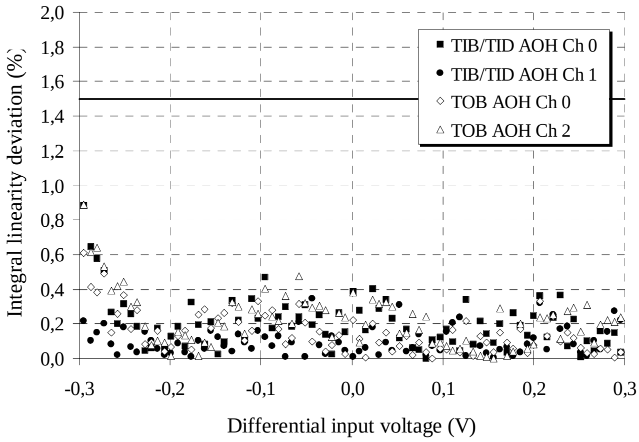
| Ch. | Gain (μW/mV) | | | |
|---|---|---|---|---|
| | LD gain 5 mS | LD gain 7.5 mS | LD gain 10 mS | LD gain 12.5 mS |
| 0 | 0.18<br>0.17 | 0.27<br>0.25 | 0.36<br>0.34 | 0.45<br>0.35 |
| 1 | 0.18<br>0.13 | 0.27<br>0.20 | 0.37<br>0.26 | 0.42<br>0.32 |

TOB AOH

| Ch. | Gain (μW/mV) | | | |
|---|---|---|---|---|
| | LD gain 5 mS | LD gain 7.5 mS | LD gain 10 mS | LD gain 12.5 mS |
| 0 | 0.14<br>0.14 | 0.20<br>0.21 | 0.28<br>0.28 | 0.35<br>0.35 |
| 2 | 0.20<br>0.16 | 0.30<br>0.24 | 0.40<br>0.32 | 0.50<br>0.39 |

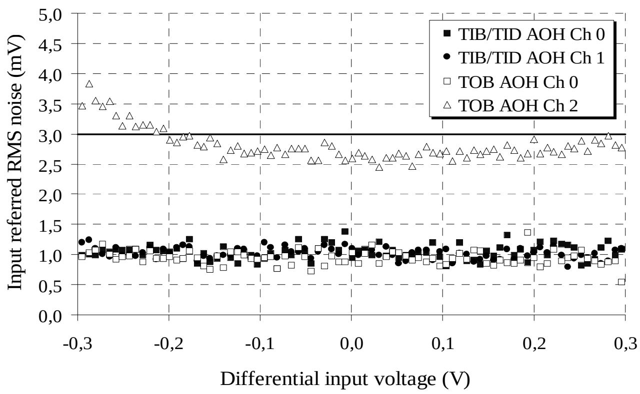



(a)

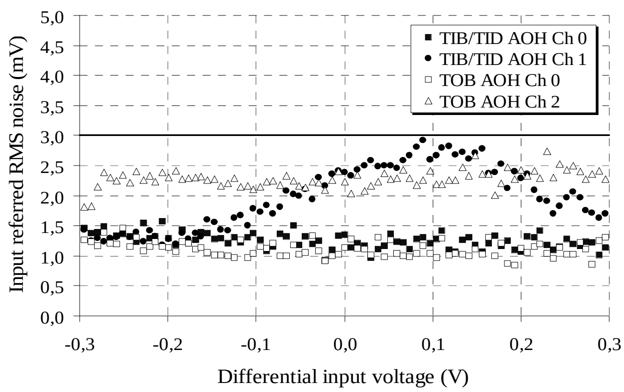



(b)

Figure 8. Integral linearity deviation on two channels of the TIB/TID and TOB AOHs before (a) and after (b) the irradiation.




(a)



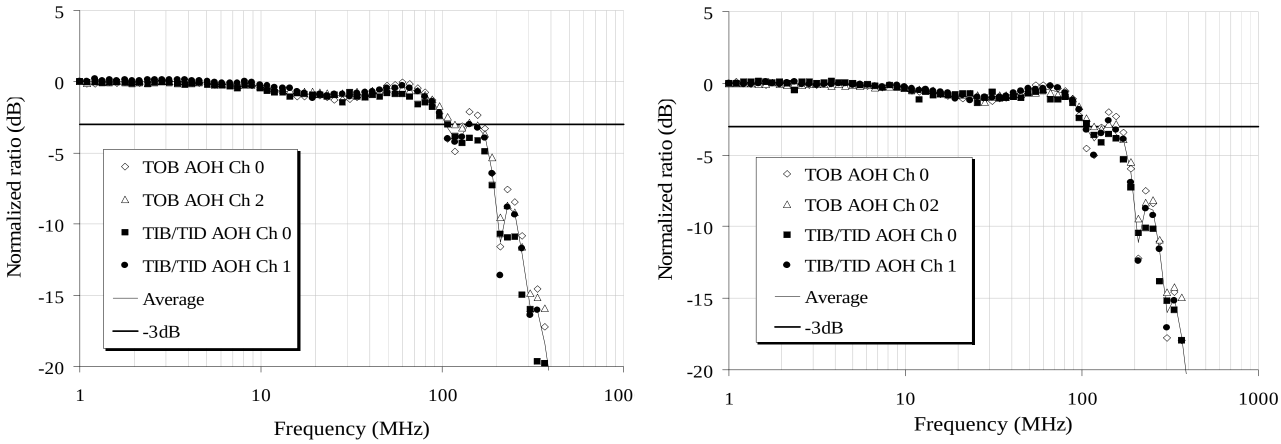

(b)

Figure 9. RMS noise on two channels of the TIB/TID and TOB AOHs before (a) and after (b) the irradiation.

The important result is that both RMS noise and INL are only weakly affected by the irradiation.

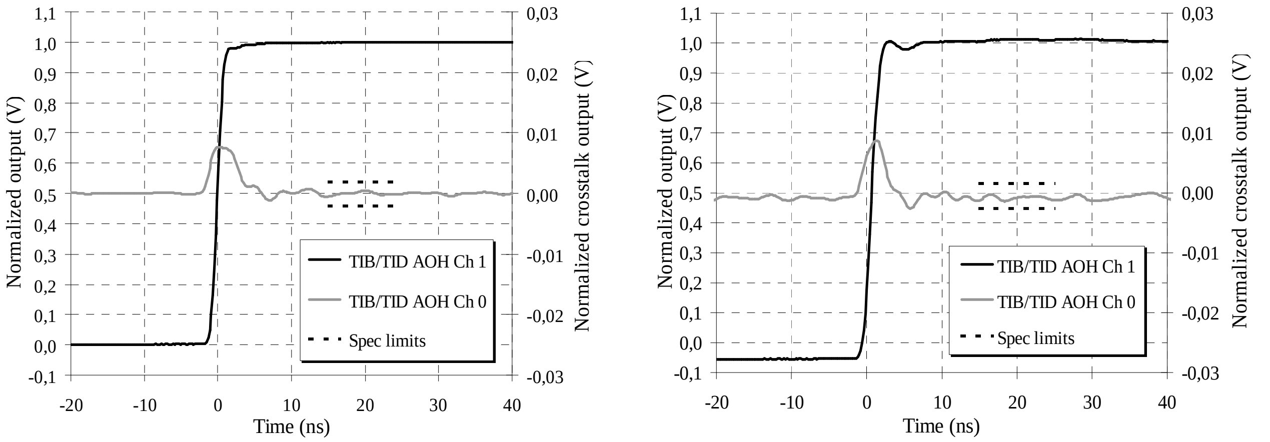
The bandwidth of the two AOH circuits was measured by generating sine waves at increasing frequencies with a Rhode & Schwartz SMX RF oscillator (range 0.1 to 1000 MHz) (see fig. 7). The optical output is converted into electrical by the high frequency photodiode (Terahertz Technologies TIA-950) and read on the digital scope (Tektronix TDS 3054, bandwidth 500 MHz). The ratio between the amplitude of the output signal and that of the input gives a measurement of the bandwidth at –3 dB. A comparison of the results obtained before and after the irradiation is reported in figure 10. The bandwidth at –3 dB (this value is indicated by the horizontal solid line) measured on the two channels of each AOH before and after the irradiation is about 100 MHz, above the minimum of 90 MHz requested by the CMS tracker optical link specifications [12]. The measured values are in fact limited by the bandwidth of the AD8192 amplifier rather than the optical link itself.

The crosstalk between the AOH channels was measured by injecting a fast input signal from the pulse generator (Agilent 81110A/81112A, rise time 0.8 ns) (see fig. 7) on one channel and measuring the corresponding output on the other after 20 ns with the scope. Figure 11 shows the crosstalk on channel 0 of the TIB/TID AOH before and after the irradiation. The limits, represented in the figure with the dashed lines, correspond to the maximum value of the crosstalk allowed by the CMS tracker specifications for the optical link of –54 dB [12].




(a) (b)

Figure 10. Bandwidth of two channels of the TIB/TID and TOB AOHs before (a) and after (b) the irradiation.




(a) (b)

Figure 11. Right axis: crosstalk measured on channel 0 of the TIB/TID AOH before (a) and after (b) the irradiation. Left axis: normalized output voltage on channel 1.

# 6 Conclusions

The irradiation of analogue opto-hybrid circuits with a proton beam of 26 MeV up to a fluence of $0.8 \cdot 10^{14}$ p/cm$^2$ has shown an increase of the laser diode threshold current of about 3 mA. Some decrease of the gain of about 14% on average was measured. The small effect on electrical parameters, like linearity, noise, crosstalk and bandwidth demonstrates the radiation tolerance of such electronic devices for proper functionality during the CMS lifetime. These low levels of damage are also consistent with earlier test results and can be easily compensated by the LLD.


## Acknowledgements

We thank A. Dierlamm and F. Hartmann of the Forschungzentrum of Karlsruhe for their collaboration and K. Gill from CERN for useful discussions about the irradiation of optical components. We are grateful to F. Casinini for his support to the test.


## References


[1] "The Tracker Project - Technical Design Report", *CERN/ LHCC 98-6 (15 April 1998) and "Addendum to the CMS Tracker TDR by the CMS Collaboration", CERN/LHCC 2000-016 (21 February 2000).*

[2] Complete informations available at the URL: *http://cern.ch/cms-opto*

[3] "Optical readout and control systems for the CMS Tracker". J. Troska et al. *To appear on Proc. of the Nuclear Science Symposium, Norfolk, VA, November 2002.*

[4] "A PMC based ADC card for CMS Tracker Readout". S. A. Baird et al. *Ref.: IEEE Real-Time '99 Conference, Santa Fe, USA.*

[5] "Design and performances of a circuit for the analogue optical transmission in the CMS Inner Tracker". M. T. Brunetti et al. *Proc. of the 7th LEB Workshop, Stockholm, pp.165-168 (2001).*

[6] "Prototype analogue optohybrids for the CMS Outer Barrel and Endcap Tracker". J. Troska et al. *Proc. of the 7th LEB Workshop, Stockholm, pp.174-178 (2001).*

[7] "The APV25 deep submicron readout chip for CMS detectors". L. L. Jones et al. *Proc. of the 5th LEB Workshop, Snowmass-Colorado (1999).*

[8] "A radiation tolerant laser driver array for optical transmission in the LHC experiment". G. Cervelli et al. *Proc. of the 7th LEB Workshop, Stockholm, pp.155-159 (2001).*

[9] K. Gill et al, Photonics for Space and Radiation Environments VIII, *Proc. SPIE Vol. 4823, pp. 19-33 (2002).*

[10] "Quality assurance programme for the environmental testing of CMS Tracker optical links". K. Gill et al. *Proc. of the 7th LEB Workshop, Stockholm, pp.160-164 (2001).*

[11] Private communications available at the URLs: *http://cms.pg.infn.it/opto/characterization.html* and *http://aoh.hephy.at/aoh_components_talk_dec2001.pdf.*

[12] "CMS Tracker Optical Readout Link Specifications. Part 2: Analogue Opto-hybrid". Version 3.2, 30 April 2001 CERN EP/CME. Available at the URL: *http://edms.cern.ch/document/312573/3.2*