

# Rad-Tol Pt-100 Isolation Amplifiers for the LHC Cryogenic System

J. A. Agapito<sup>1</sup>, J. Casas-Cubillos<sup>2</sup>, A. Fernandes<sup>3</sup>, F. J. Franco<sup>1</sup>, I. Goncalves<sup>3</sup>, A. H. Cachero<sup>1</sup>,  
J. Marques<sup>3</sup>, M.A. Rodríguez-Ruiz<sup>2</sup> and Y. Zong<sup>1</sup>

<sup>1</sup>Dep. Física Aplicada III, Fac. Ciencias Físicas, Universidad Complutense (UCM), Madrid (Spain)

<sup>2</sup>CERN, AT Division, Geneva, (Switzerland)

<sup>3</sup>Instituto Tecnológico e Nuclear (ITN), Sacavém (Portugal)  
agapito@fis.ucm.es

## Abstract

The cryogenic system of the LHC will use Pt-100 sensors to measure temperatures between 40-300 K and isolation devices will be used. The selected commercial components must be rad-tolerant since a total radiation dose of  $5 \cdot 10^{12}$  n/cm<sup>2</sup> & 100 Gy is expected during ten years of the LHC lifetime. Neutron tests in this family of devices were performed and the results are shown in this paper.

## I. ISOLATION FOR HTS LEADS

The temperature of the HTS leads in the cryogenic system of the LHC will be monitored by means of PT-100 sensors. These sensors are *Pt* resistors whose resistance at 273 K is 100 Ω and with a lineal dependence on the temperature.

The working temperature of the HTS leads is supposed to be between 40-300 K so the value of PT-100 resistance will vary approximately between 10-100 Ω. The uncertainty margin is 1.5 Ω and the DC voltage between HTS leads and ground could reach 1900 V. Also, the use of additional isolated regulators should be avoided although this is not compulsory.

Finally, the background radiation will affect the electronic devices. Theoretical simulations have shown that the expected total radiation dose will cause a displacement damage of  $5 \cdot 10^{12}$  n/cm<sup>2</sup> and a total ionising dose of 100 Gy within 10 years of LHC functioning.

Therefore, the development of the HTS leads measuring system will require commercial isolation devices (either isolation amplifiers or signal conditioner) whose characteristics fit the electrical specifications of the cryogenic system and that tolerate the expected total radiation dose.

## II. DESCRIPTION OF TESTED ISOLATION DEVICES

The isolation between input & output stage is usually done by means of three kinds of devices: Optocouplers, coupling transformers or capacitors [1]. Optical isolators were discarded because of the well-known sensitivity of these devices to displacement damage [2].

Tested devices were manufactured by Analog Devices (AD) and Texas Instruments (TI). Coupling transformers is the isolation system preferred by AD but, on the contrary, TI is in favour of using capacitors to isolate the different stages. The set of tested candidates are shown in Table 1.

Most of the used AD devices are included in the category of isolation amplifiers. This means that the input stage is an isolated operational amplifier with external passive devices, as resistors and capacitors, connected to a modulator that transmits the opamp output value to the other stage through a coupling transformer (Figure 1).

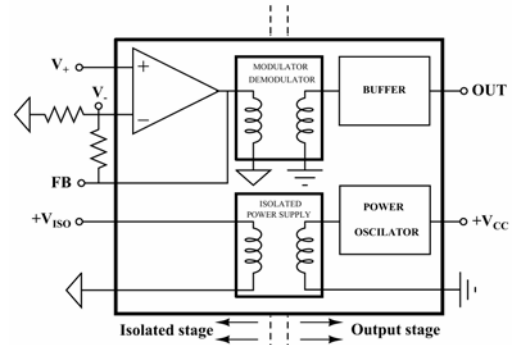


Figure 1: Typical structure of Analog Devices' isolation amplifiers. Coupling transformers allow the communication between isolated stages. Additional resistors determine the DC gain of the system.

Based on this kind of devices, 1B41 signal conditioner can measure the value of a PT-100 resistor in the interval of temperatures  $[T_L, T_H]$  (Figure 2). This device provides an output voltage with a value proportional to the difference between  $R_{TD}$  (PT-100 sensor) and  $R_Z$ , reference resistor with a value equal to  $R_{TD}$  at  $T = T_L$ .

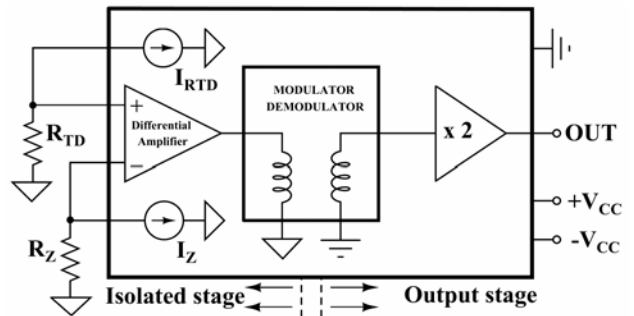


Figure 2: Simplified internal topology of 1B41 signal conditioner. The gain of the differential amplifier is determined by external resistors. Isolated voltage sources, present in the actual device, are not included in this schema.

Table 1: *Tested Isolation Devices*

Model	Manufacturer	Kind	Internal Isolated Regulators?	DC Isolation	Main Characteristics
AD202	AD	Isolation amplifier	Yes, $\pm V_{ISO}$	$\pm 2000$ V	Low cost, miniature, unipolar supply
AD204	AD	Isolation amplifier	Yes, $\pm V_{ISO}$	$\pm 2000$ V	Similar to AD202 but with external clock signal, provided by AD246 (also tested)
AD210	AD	Isolation amplifier	Yes, $\pm V_{ISO}$ & $\pm V_{OSS}$	$\pm 3500$ V	Precision, wide bandwidth, 3-port
AD215	AD	Isolation amplifier	Yes	$\pm 1500$ V	120 kHz bandwidth, low distortion
1B41	AD	Signal conditioner	Yes	$\pm 1500$ V	Very few additional external devices
ISO122	TI	Isolation buffer	No	$\pm 1500$ V	Precision lowest cost
ISO124	TI	Isolation buffer	No	$\pm 1500$ V	Precision lowest cost

Finally, devices from Texas Instruments (Figure 3) are quite different from previous components. The main differences are the necessity of two pairs of isolated power supplies and the fact that the gain is always 1.

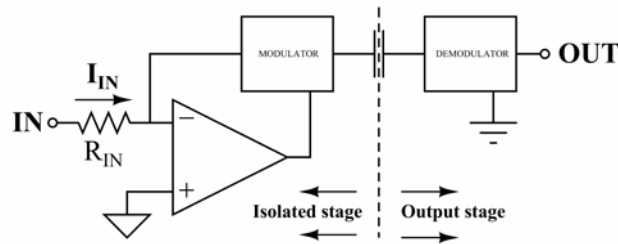


Figure 3: *Simplified internal structure of ISO12X devices. Theoretically, the value of  $R_{IN}$  is 200 k $\Omega$ .*

### III. TEST SETUP

#### A. Irradiation facility at ITN

The irradiations were performed using a dedicated irradiation facility in the Portuguese Research Reactor. The components under test were mounted on several PCBs, in a simple support placed inside a cylindrical cavity created in one of the beam tubes of the reactor, thermally conditioned. For these experiments, the reactor was operated at the power of 400 kW. The fluence of  $5 \cdot 10^{12}$  n/cm<sup>2</sup> in the central PCB was reached in 30 h, during three days.

A 0.7 cm thick boron shield cut the thermal neutron component of the beam and a 4 cm thick Pb shield was used to reduce the total gamma dose to the order of 100 Gy for the central PCB. The neutron fission fluxes were measured with <sup>58</sup>Ni detectors placed at the centre of the boxes that contained

the PCBs. A photodiode sensitive to neutrons was placed in several boards, so that the neutron flux was monitored online. A channel for monitoring the gamma radiation by means of an irradiation chamber was also implemented.

#### B. Device electrical parameters and on-line measuring system

All the isolation amplifiers from Analog Devices (Figure 1) can be divided into several sections: Isolated operational amplifier, isolated power supplies and output stage. Therefore, the characterization of the whole isolation amplifier is carried out in three parts:

a) *Parameters of the op amp*: Like other operational amplifiers, that present in the isolated stage has an input offset voltage,  $V_{IOS}$ , and input bias currents,  $I_{B+}$  &  $I_{B-}$ . Their values can be calculated from the voltages at the output FB and the inverting & non inverting inputs at several specific feedback networks. Also, it is very interesting to describe the transfer function between  $V_{IN}$  &  $V_{FB}$  by means of the DC gain, which depends on the external resistors and the open loop gain, and the typical output error.

b) *Isolated internal regulators*: Mean & ripple voltages.

c) *Transmission efficiency* The voltages of FB and OUT: in an ideal isolation amplifier are equal. However, in a real one, the relationship becomes  $V_{OUT} = TC \cdot V_{FB} + V_{OUT,OS}$ , where TC is the transmission coefficient (ideally 1) and  $V_{OUT,OS}$ , the offset voltage related to the output stage.

On the contrary, ISO12X amplifiers are much simpler (Figure 3) so few parameters are needed to describe their functioning. The most important parameters are the DC gain,  $G$ , and the output offset voltage,  $V_{OUT,OS}$ , since they are needed to calculate the output value from the input

( $V_{OUT} = G \cdot V_{IN} + V_{OUT,OS}$ ). Moreover, the value of  $R_{IN}$  is easily measured comparing it with an external resistor.

Finally, the special characteristics of 1B41 make its radiation tests a little different from other amplifiers. In this case, we preferred to test the device while it was measuring a known resistance and register its output during the irradiation. So, a large number of devices were irradiated in order to know the output value with several resistors with values between 10–100  $\Omega$ , playing the role of  $R_{TD}$  sensors.

In any case, the measure of each parameter requires different resistor networks. This problem was solved using several mechanical relays that, after switching, could change the feedback network of the device. An automatic PC system, consisting of a PC, multimeter, switch array, controlled voltage sources and power supplies, managed to select the device and to measure its main characteristics every 10 minutes during the irradiation. The computer analysed the data and extracted the most interesting parameters of the devices. The set of data were stored in the computer for a later analysis.

#### IV. RESULTS ON AD2XY ISOLATION AMPLIFIERS

This data were measured during the irradiation while the devices were biased with  $\pm 15$  V power supplies. In order to select the best device, two samples of every model were tested and, afterwards, the most-tolerant one was determined and a second campaign was centred in the study of this device.

##### A. DC input parameters

Input offset voltage and bias currents of the isolated operational amplifier are included in this category. Input offset voltage of all the devices except AD215 hardly changes during the irradiation (Figure 4). On the contrary, AD215 amplifier shows a great increase in this parameter (Figure 5).

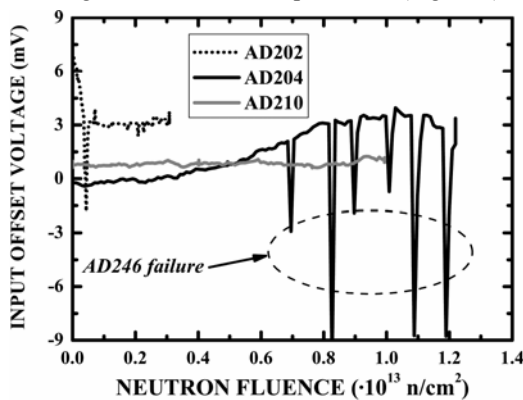


Figure 4: Evolution of  $V_{10S}$  in several AD isolation amplifiers. Peaks in AD204 dashed line are related to transitory failures of the external clock driver, AD246.

Input bias currents of these amplifiers, except AD215, were not significantly affected by this radiation. AD215 suffered a large increase of these parameters, as figure 5 shows.

##### B. DC gain in input stage

This parameter was measured in two situations: First of all, the amplifier was configured as a buffer with unity gain and, finally, a pair of resistors with values of 22 & 220 k $\Omega$  set the gain into a value about 11. The edge values of the input data sweep were selected in order to obtain *output* data between  $\pm 1$  V.

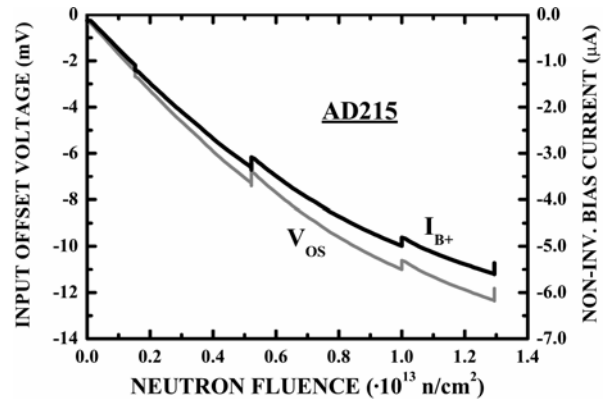


Figure 5: Evolution of DC input parameters of AD215.

In an ideal operational amplifier, this parameter is only related to the value of feedback resistors but, in the real ones, there is a small dependence on the open loop gain. This parameter decreases as neutron fluence increases [2] but this is not a serious handicap in amplifiers with a high open loop gain (AD210, AD215). However, other amplifiers as AD202 & AD204 have a quite low initial value so the final value will be even lower. This fact leads to measure a value of DC gain below the theoretical one. E. g., an AD202 sample showed an input DC gain of 10.92, instead of the theoretical value, 10.97, after receiving  $1.2 \cdot 10^{13}$  n/cm<sup>2</sup>.

##### C. Transmission coefficient

This parameter is the ratio between the output & input gain and it is related to the gains of the modulator/demodulator and output buffer. Ideally, its value is 1 although it is usually a little lower. All the amplifiers showed a decrease in this parameter, very important in AD202 & AD204 (Figure 6).

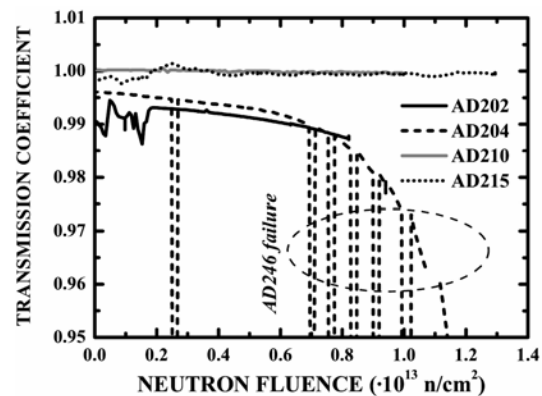


Figure 6: Transmission coefficient in AD's isolation amplifiers. Discontinuities in AD204 plot are related to AD246 failures.

### D. Output offset voltage

Usually, this parameter hardly shifts during the irradiation. The only exception is AD215, where there is an increase about  $5 \text{ mV}/10^{12} \text{ n/cm}^2$  (Figure 7).

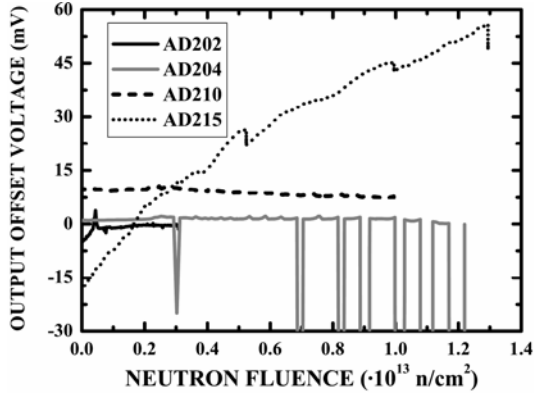


Figure 7: Output offset voltage,  $V_{OUT,OS}$ , in AD's amplifiers.

### E. Typical output error

This parameter allows to estimate the non-linearity of the function  $V_{OUT} = f(V_{IN})$ . According to our criterion, this is the highest difference between the actual value of  $V_{OUT}$  and the ideal one calculated from  $V_{IN}$ , DC gain, offset voltages, etc.

It hardly changes during the irradiation so we deduce that there is no relationship between this parameter and the neutron fluence. The exact value depends on the DC gain since, usually, the higher the gain, the higher the error value. Table 2 shows the average values measured during the irradiation.

Table 2: Typical error value of AD's isolation amplifiers

Model	DG Gain = 1	DC Gain = 11
AD202	0.3	1.3
AD204	0.15	0.4
AD210	0.03	0.1
AD215	0.1	0.2
	mV	mV

### F. Isolated regulators

During the irradiation, the mean & rms ripple voltages of each internal isolated power supply were measured. None was loaded with external resistors. The initial output values were about  $\pm 7\text{-}8 \text{ V}$  in AD20X and  $\pm 15\text{-}16 \text{ V}$  in AD21X.

There is a growth of the DC output value. E.g., an AD210 showed an increase of  $+V_{ISO}$  from  $16.2 \text{ V}$  to  $16.8 \text{ V}$  when the neutron fluence reached the value of  $10^{13} \text{ n/cm}^2$ . Similar shifts were found in the rest of devices. On the contrary, the ripple voltage decreases in all the devices. E.g., the previous device changed from  $325 \text{ mV rms}$  to  $250 \text{ mV rms}$  after the irradiation.

### G. Evolution of AD246

This device is an external clock driver whose purpose is to provide a  $0\text{-}15 \text{ V}$  square signal to supply AD204. During the irradiation, average and rms values were measured to find out the tolerance of the device.

Due to the duty cycle is 50%, both values must be ideally  $7.5 \text{ V}$ . Figure 8 shows the evolution of these parameters during the irradiation. We observed that the device suffers transitory disruptions above  $7\text{-}8 \cdot 10^{12} \text{ n/cm}^2$ . The consequences of these strange disruptions were found in the output of AD204 as well.

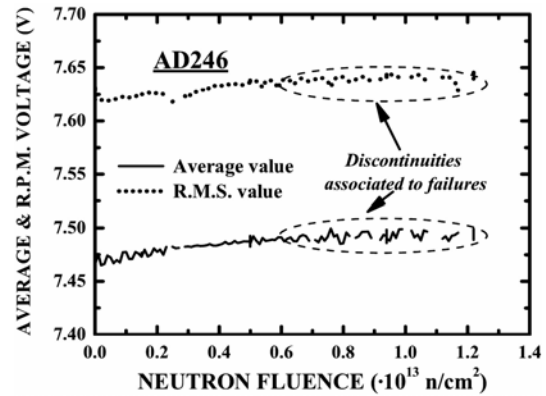


Figure 8: Evolution of AD246 output during the irradiation.

## V. RESULTS IN 1B41 SIGNAL CONDITIONER

Six samples of this device were irradiated while they were measuring reference resistors of  $10, 47$  and  $100 \Omega$ . During the irradiation, they were biased with  $\pm 15 \text{ V}$  power supplies.

We found that these devices are hardly affected by the radiation below  $7\text{-}8 \cdot 10^{12} \text{ n/cm}^2$  (Figure 9). If it exceeds this level, the output voltage value begins to increase very quickly and, finally, the device stops working when the neutron fluence reaches a value depending on the sample. E.g., a sample could not tolerate a neutron fluence of  $9 \cdot 10^{12} \text{ n/cm}^2$  although another one lasted up to  $1.8 \cdot 10^{13} \text{ n/cm}^2$ .

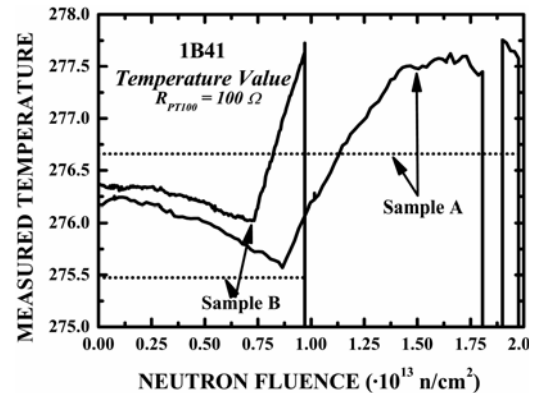


Figure 9: Temperature measured by 1B41 ( $RTD = 100 \Omega$ ). Dashed lines are the exact temperature that they had to determine.

The most tolerant parts of the device are the internal current sources  $I_{RTD}$  &  $I_Z$ , which can tolerate a neutron fluence above  $1.5 \cdot 10^{13}$  n/cm<sup>2</sup> and, eventually, these parts fail at  $2.5 \cdot 10^{13}$  n/cm<sup>2</sup>.

According to our tests, the lower the values of the resistors, more accurate are the measures. This fact might be related to a shift of the DC gain value of the internal stages, whose effect would be negligible with very low input voltages but more and more important as the input voltage increases.

## VI. RESULTS IN ISO12X ISOLATION AMPLIFIERS

These amplifiers were tested with a couple of power supplies of  $\pm 15V$ . ISO122 & ISO124 amplifiers are very similar (same internal structure, package, etc.) and the main difference is the highest accuracy of ISO124.

The input resistor,  $R_{IN}$ , was measured during the irradiation but no shift was found below the highest value of neutron fluence ( $1.71 \cdot 10^{13}$  n/cm<sup>2</sup>). This measure also showed that the input resistor of ISO124 is more accurately built than ISO122. The measured values in these devices were between 170-200 k $\Omega$  whereas the ISO124 ones were between 198-200 k $\Omega$ .

Output gain value of ISO124 hardly changes during the irradiation. In this device, we measured random oscillations around 1, never larger than 0.4 %. On the contrary, the DC gain of ISO122 changes as the irradiation takes place. E.g., a sample that received the highest neutron fluence ( $1.71 \cdot 10^{13}$  n/cm<sup>2</sup>) showed a final DC gain value of 0.992 instead of the original one, 1.000 (Figure 10).

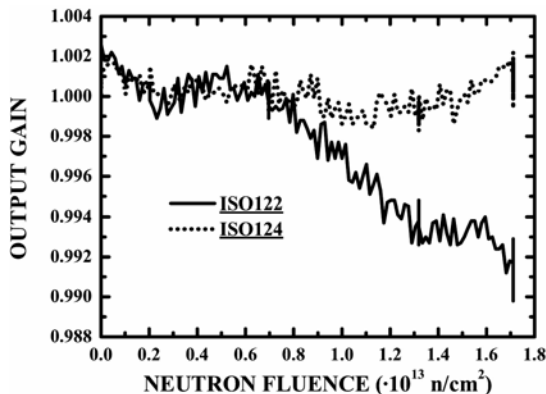


Figure 10: Output gain of ISO12X amplifiers

Finally, output offset voltage increases during the irradiation although it may be random: Some samples show a positive value while, in other ones, the value of output offset voltage is negative (Figure 11). In any case, the largest shifts were found in the ISO122 samples.

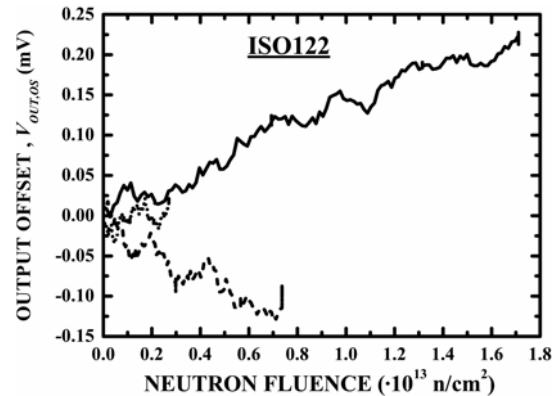


Figure 11: Output offset voltage of irradiated ISO122 amplifiers.

## VII. CONCLUSIONS

The results shown in this paper set that some isolation devices are not suitable for the specific use in the LHC cryogenic system. These devices, and reasons to refuse them, are the following:

- AD202 & AD204*: Very sensitive DC gain values.
- AD215*: Large increase of input bias currents.
- ISO122*: It should be discarded on behalf of ISO124

According to our tests, 1B41 can tolerate a total radiation dose of  $7\text{-}8 \cdot 10^{12}$  n/cm<sup>2</sup>, which is a 50 % higher than the expected dose. Also, the AD210 isolation amplifier could be an adequate candidate to be used in the LHC cryogenic system because of two reasons: An acceptable tolerance to radiation and a set of very good characteristics. A later radiation test on six additional samples confirmed the results shown in previous sections. Also, other paper was found in the scientific literature that support the results shown in this paper [3]. Finally, ISO124 amplifier shows a good tolerance to radiation. However, the drawback of the necessity of additional power supplies still remains so it should be considered a second option if 1B41 & AD210 were refused.

## VIII. REFERENCES

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