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Review

Radiation tolerant D/A converters for the LHC cryogenic system

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Abstract

The electronic instrumentation of the Large Hadron Collider (LHC) cryogenic system is expected to receive a large radiation dose ($>10^{13}\,\mathrm{n\,cm^{-2}}$ and 1–2 kGy (Si)) within 10 years of activity so all the electronic devices should tolerate this radiation level without a significant degradation.

This paper focuses on the selection of a radiation tolerant 12-bit parallel input D/A converter suitable for the signal conditioners for cryogenic thermometry in the LHC. During an initial campaign, some candidate converters were irradiated to determine the most tolerant device. Once this was determined, a massive test was carried out. Some weak points of the selected device were addressed through the use of an external voltage source and a radiation tolerant operational amplifier. The tests show that a system consisting of an AD565 D/A converter, coupled to an external voltage reference and an OPA627 operational amplifier can tolerate a total radiation dose up to $5\times10^{13}\,\mathrm{n\,cm^{-2}}$ and 2100 Gy (Si), thus satisfying the requirements set by CERN.

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Keywords: COTS; D/A converters; Instrumentation; Radiation damage

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Contents

1. Introduction

Temperature measurement is a key issue in the Large Hadron Collider (LHC), as it will be used to regulate the cooling of the superconductor magnets. An absolute accuracy of 10 mK, below 2.2 K, and 5 K above 25 K is necessary. For resistive thermometers covering the full temperature range this is typically equivalent to a relative accuracy dR/R of 3×10^{-3} over 3 resistance decades. On the other hand, the sensing current is limited to a few mA to reduce the thermometer's self-heating. Since commercial signal conditioners cannot meet these stringent requirements, different architectures had to be developed at CERN [1]. Additionally, the signal conditioners will operate in a radiation environment and radiation-tolerant parts must be used. As a part of the collaboration agreement between the Accelerator Technology Division of CERN and the Universidad Complutense of Madrid, the selection of a digital-to-analog (D/A) converter to be used in the development of the temperature control system has been performed and the results are shown in this work.

The requirements for the D/A converter were as follows: 12 parallel inputs and tolerance to the background radiation originated from the particle beam. Previous simulations have predicted a leakage of neutrons, charged particles and gamma rays from the inner parts of the collider [2] so the electronic instrumentation will be affected by this radiation. The maximum expected total dose for a period of 10 years, including safety factors, is predicted to be $5 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ for neutrons (1 MeV equivalent) and 1–2 kGy (Si) for gammas [3]. The energy spectrum of the neutrons is expected to be similar to the one of the fission of ^{235}U, with the highest intensity in the 1–2 MeV region. Radiation tests were carried out at the Portuguese Research Reactor (RPI), using a facility designed to reproduce the LHC radiation environment [4]. The devices received neutron fluences in the $2\text{–}5 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ range and a gamma dose in the 1.2–2.1 kGy (Si) range in five up to eight sessions of 12 h followed by a 12-h interval, due to the working schedule of the reactor.

At the beginning of the study, two lines were explored: fast bipolar, as well as CMOS technology devices. However, the results obtained with CMOS devices were not as good as expected due to TID damage [5] so this line was abandoned, in favour of bipolar technology.

2. Irradiation facility

The RPI is a 1 MW, light-water moderated reactor working since 1961. A dedicated dry irradiation facility was built around one of the beam tubes, with an irradiation chamber with $100\,\mathrm{cm} \times 60\,\mathrm{cm} \times 60\,\mathrm{cm}$ ($l \times w \times h$) at the end of the tube, as well as a prolongation inside the beam tube, made through the introduction of a 100 cm long cylinder with 150 mm inner diameter, attached to the face of the beam tube housing. The neutron beam size is 150 mm, as defined by the diameter of the beam tube close to the core [4]. The shielding of the facility is a combination of polyethylene lined with Cd and high-density concrete. Insertion and removal of the circuits are done when the reactor is stopped and the beam tube flooded. The arrangement of the outer radiation shield allows the use of relatively short connecting cables (ca. 4 m) to the measuring instruments.

In order to obtain a neutron/photon ratio close to the one expected for the location of the signal conditioners at the LHC, a Pb filter was placed inside the irradiation tube to reduce the gamma field and a Boral filter to reduce the thermal neutron component. The neutron spectrum in the irradiation facility is essentially a leakage spectrum in a light-water moderated ^{235}U fission reactor. The energy distribution of fission neutrons is highly asymmetric, with most neutrons in the 1–2 MeV range. Although there are still neutrons with energy in excess of 10 MeV, these contribute only about 0.1% of the total neutron flux above 1 MeV. The actual spectrum in the irradiation cavity was simulated using the Monte-Carlo code MCNP-4C, using a detailed three-dimensional model of the core validated with extensive measurements in the core region [6]. The calculated spectrum was further adjusted to activation measurements using sets of foils with different energy-dependent cross sections, following a procedure previously described [7].

Fig. 1 shows the adjusted spectrum per lethargy unit, inside the irradiation chamber, at the point closest to the core. A spectrum corresponding to a core position close to the entrance of the beam tube is also shown for comparison. The removal of a significant part of the thermal neutron component is clearly visible. At the point closest to the core in the irradiation cavity the neutron fluxes are: fast neutron flux of $1.0 \times 10^9\,\mathrm{n\,cm^{-2}\,s^{-1}}$ ($E > 1$ MeV), epithermal flux of $4.0 \times 10^7\,\mathrm{n\,cm^{-2}\,s^{-1}}$ ($E = 1$ eV) and thermal of $2.7 \times 10^8\,\mathrm{n\,cm^{-2}\,s^{-1}}$ ($E < 0.5$ eV).

During irradiations, the fast neutron fluxes were measured with Ni foils, considering the averaged neutron cross-section for the $^{58}Ni(n,p)\,^{58}Co$ reaction in a fission spectrum. The ^{58}Co isotope has a half-life of 70.78 day, which is convenient for an activation taking several days. For the neutron spectrum in the irradiation cavity, the fluences obtained in this way with the Ni foils are 40% higher than the total fluence above 1 MeV, determined using multiple foils as described in Ref. [7].

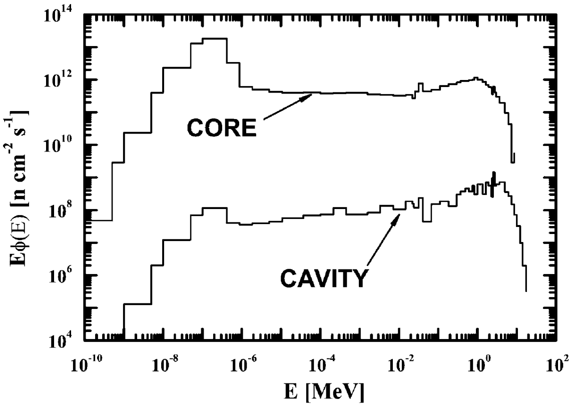

Fig. 1. Neutron spectrum per lethargy unit inside the irradiation chamber, at the point closest to the core. The spectrum corresponding to the core is also shown for comparison.

The fluences in the irradiation of electronic devices are normally expressed in terms of a 1 MeV neutron equivalent neutron fluence for Si. Following the procedure detailed in Ref. [8], the hardness parameter in the irradiation cavity was determined to be 0.81(5). The equivalent 1 MeV fluence is 78% higher than the total flux above 1 MeV, i.e., 28% higher than the fluence determined with the Ni foils. In this paper, all fluences in the results below are expressed in terms of the Ni foils and they can be expressed in terms of its 1 MeV equivalent by multiplying the values by a 1.28 factor.

3. Device characterization system

The system used to characterise the devices during the irradiation consisted of a personal computer (PC), where a program developed in Testpoint® controlled several instrumentation devices using the standard GPIB protocol: a Keithley 7002 switching system, a Keithley 2002 digital multimeter and a Keithley 236 source measure unit. Digital inputs are provided by the

PC by means of a digital PIO12 card, also managed by the program. The PC could determine the main parameters of the converters every few minutes during the irradiation and stand-by periods. This automatic system was continuously working for periods of 5–10 days, without interruptions. The devices under irradiation were placed on test boards, connected to the digital multimeter and to the power supplies by a low resistance and shielded 4-m cable. All instrumentation devices were supplied by an uninterruptible power source in order to minimise the action of unexpected power failures.

A digital input sweep was made by the program in order to determine the main non-idealities of the DACs: offset and gain errors and the relative number of bits, N_{REL}, which is a useful parameter to calculate the non-linearity of the DAC. Complete information about these parameters can be found in Ref. [9]. The devices selected for the test were AD565AJD, AD667JN (Analog Devices) and DAC703KH (Texas Instruments), whose datasheets are available on the manufacturers' websites [10,11].

The offset and gain errors were calculated in units of LSB. This unit is defined as $1\,\mathrm{LSB} = \mathrm{range}/2^N$, where *range* is, in most cases, a reference voltage and N the number of inputs. Usually, bipolar DACs have an implemented voltage source to be used as a reference; e.g., on the AD565AJD and AD667JN converters, the integrated voltage reference is 10 V and this is the range value, so $1\,\mathrm{LSB} = 2.44\,\mathrm{mV}$. In contrast, for the DAC703KH, the value of its reference voltage is 6.3 V although the actual output range is 20 V, so $1\,\mathrm{LSB} = 4.88\,\mathrm{mV}$.

Unlike the other devices, the AD565AJD has a current output so it needs an operational amplifier (op amp) to convert its output into voltage. Usually, the op amp is placed close to the converter but, in order to avoid that its predictable degradation would be attributed to the converter, it was placed outside the irradiation cavity. After the irradiation, other parameters such as the modification of the power consumption and the frequency behaviour were checked. Finally, the temperature inside the cavity was monitored during the irradiation and kept between 30 and 35 °C.

Thus, this work complies with the standard CERN protocols concerning the set-up of neutron tests on electronic devices [12].

4. Radiation test results

4.1. Analog devices AD565AJD

During an initial test, several samples of this device received a fast neutron fluence between 2.5×10^{13} and $3.3 \times 10^{13}\,\mathrm{n\,cm^{-2}}$, with a gamma dose between 1.2 and 1.3 kGy. The conclusion of this test was that the most sensitive parameter was the internal voltage reference, where an increase of about $32\,\mathrm{mV}/10^{13}\,\mathrm{n\,cm^{-2}}$ was observed, as shown in Fig. 2. This phenomenon can be related to the increase of the line regulation coefficient, very common in irradiated voltage references. When the neutron fluence was about $2.6\text{–}2.7 \times 10^{13}\,\mathrm{n\,cm^{-2}}$, the output voltage suddenly plunged to 8.0 V. This sudden decrease was followed by a slower decrease until the end of the irradiation, when a final value of 6.9 V was reached. Some days later, the voltage output returned to a value about 10 V, most probably due to a partial recovery of the semiconductor lattice. The observed drop during irradiation is most probably due to the degradation of the operational amplifier

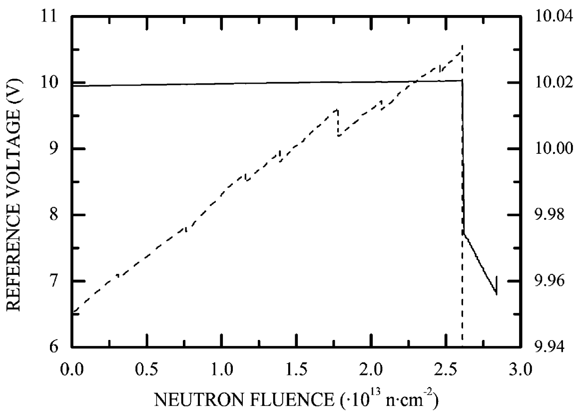

Fig. 2. Evolution of the voltage reference of the AD565AJD. The continuous line shows the evolution of the parameter all over the full range of values and is related to the *Y*-axis on the left. The dashed line is a zoom of the parameter when its value is around 10 V and the scale is shown on the right side.

attached to the voltage reference, as the authors have reported on a previous study of these components [13].

In contrast, the offset and gain errors remained almost constant during the irradiation. The only exception was a sample that underwent a sudden increase of the gain error up to 1000 LSB at a neutron fluence about $2.7 \times 10^{13}\,\mathrm{n\,cm^{-2}}$; this increase was not found in other samples. Besides, the initial relative number of bits was about 11 and was not affected by the radiation. This variation is related to the degradation of the internal voltage reference, which had previously fallen to 7–8 V. Examining the internal AD565 structure, it is evident that the highest voltage output is the reference voltage. Thus, in spite of the fact that the expected device output voltage is 10 V for an input of 4095, the actual output is about 7–8 V. In other words, the gain error is 2–3 V, which corresponds to about 800–1200 LSB, thus explaining the observed variation.

Also, a slight decrease was observed on the supply current. For example, on a sample that required a supply current of 12.7 mA before the irradiation, this value decreased to 11.1 mA after an irradiation to a neutron fluence of $3.3 \times 10^{13}\,\mathrm{n\,cm^{-2}}$. Finally, before the irradiation, the converter output took 120 ns to change from -10 to 0 V and this value was not changed in any device after the irradiation. Therefore, we conclude that there is no significant change in the frequency response at this level of radiation.

4.2. Analog devices AD667JN

Like the previous converter, the samples of these devices showed an increase of the reference output voltage. Nevertheless, the increase was only 10–12 mV (Fig. 3) in the samples irradiated to a higher fluence ($\sim 2.8 \times 10^{13}\,\mathrm{n\,cm^{-2}}$). In these devices, the offset error was the most affected parameter. When the neutron fluence was $0.8–0.9 \times 10^{13}\,\mathrm{n\,cm^{-2}}$, the offset error soared from 0–1 LSB up to 22 LSB (Fig. 4). Afterwards, the error continued to increase, but at a lower rate and, eventually, a top value of 40–45 LSB was reached at $1.3 \times 10^{13}\,\mathrm{n\,cm^{-2}}$. Later on, the higher the neutron fluence, the lower the offset error. During the subsequent stand-by intervals, the offset error increased.

This evolution was not observed in the gain error, which remained fairly constant, with only a small decrease of $\sim 1\,\mathrm{LSB}/10^{13}\,\mathrm{n\,cm^{-2}}$. The relative number of bits decreased in proportion to the neutron fluence, although its value never became lower than 12.5 in all samples, which is above the requirements. A decrease of power supply current and a worsening of frequency response were

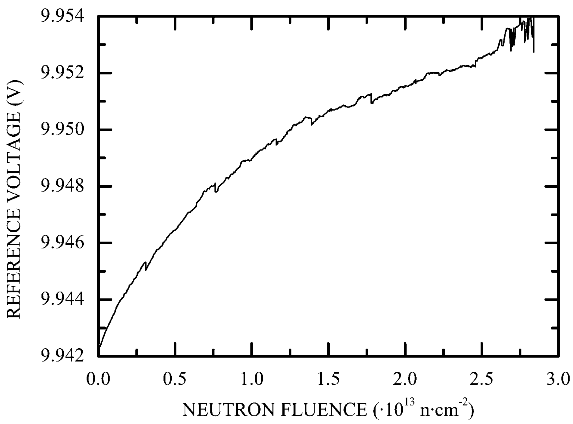

Fig. 3. Evolution of the internal voltage reference of the AD667JN.

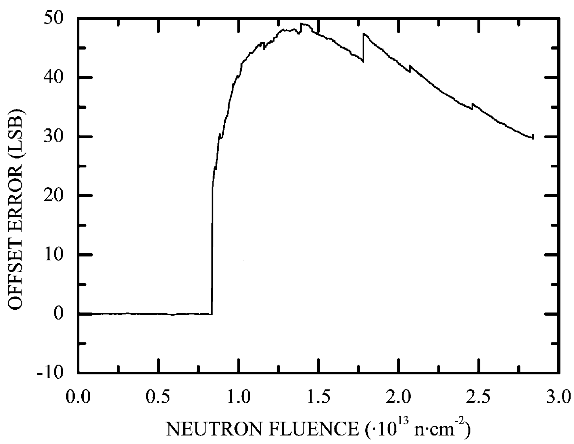

Fig. 4. Evolution of the offset error of the AD667JN. A large increase of 22 LSB at a fluence $8 \times 10^{12}\,\mathrm{n\,cm^{-2}}$ was observed during the irradiation. The small jumps of the graph result from partial annealing during the stand-by intervals and their origin is not related to the first sudden increase.

observed after irradiation. The power supply current decreased from 19.76 to 17.50 mA on the devices irradiated to a higher dose. The degradation of the frequency response is much more important: before the irradiation, the output took about 0.5 μs to change from 0 to 10 V, while after irradiation it took at least 7 μs.

4.3. Texas instruments DAC703KH

Two samples of this device received $3.3 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ and 1.3 kGy. This is a 16-bit converter so the four least significant bits were grounded to adapt the device to the 12-bit digital card of the measuring system. The voltage reference output is about 6.3 V and, unlike the other converters, it is not directly related to the value of the full-scale range, which begins at 10 V and ends at −9.9951 V. During the irradiation, the behaviour of this voltage reference (Fig. 5) did not follow the same evolution of the other devices as the value of the voltage decreased with the neutron fluence.

The offset error hardly increased at the first stage of the irradiation but, when its value was about 20 LSB, it underwent a sudden increase, as shown in Fig. 6. This threshold value was reached at a neutron fluence in the range of $1.8 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ to $2.6 \times 10^{13}\,\mathrm{n\,cm^{-2}}$, depending on the sample. Whatever the neutron fluence threshold, the increase rate was always higher than $100\,\mathrm{LSB}/10^{12}\,\mathrm{n\,cm^{-2}}$. The evolution of the gain error was quite similar to one of the offset errors. The evolution of the relative number of bits is shown in Fig. 7, where we can observe a sudden decrease simultaneously with the beginning of the offset error increase.

The decrease of the relative number of bits arises from the change of the input–output function. Fig. 8 shows the relationship between the input and the output values at different fluence levels. Before the irradiation, the function was a straight line from 10 to −10 V. Upon irradiation this function becomes a broken line since input values which are lower than the offset error cannot be correctly converted. Thus, the function is nonlinear and causes a dramatic drop of the relative number of bits. This fact explains also the increase

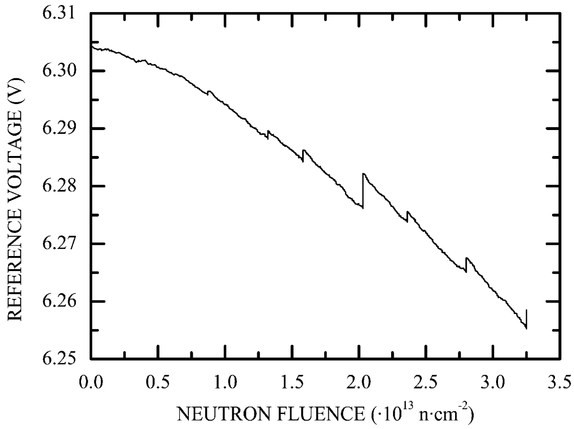

Fig. 5. Evolution of the voltage reference of the DAC703KH converter. The sharp increases of the voltage reference result from partial annealing during the stand-by intervals.

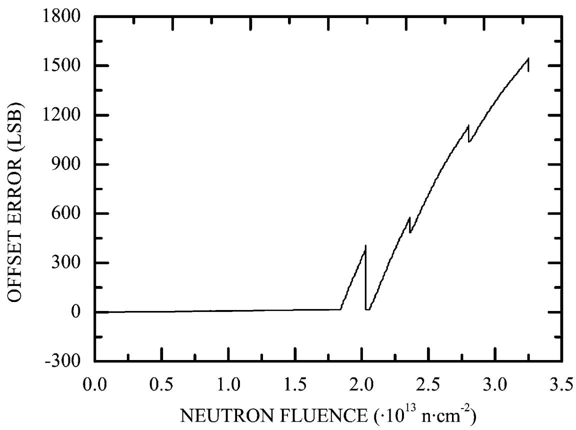

Fig. 6. Evolution of the offset error of the DAC703KH. The fast decreases of the offset error result from partial annealing during the stand-by intervals.

of the gain error due to its mathematical dependence on the offset error [9].

5. Physical origin of degradation of devices

In most situations, the change of the characteristics cannot be accurately explained without a detailed knowledge of the internal structure of the device. Unfortunately, this information is proprietary and the manufacturers are reluctant to share

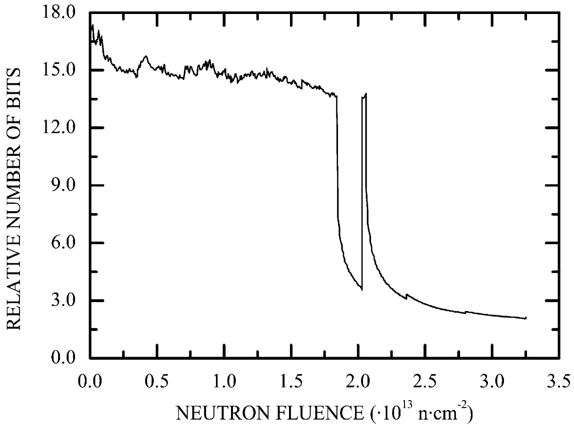

Fig. 7. Evolution of the relative number of bits on irradiated DAC703KH. The fast increase observed around $2 \times 10^{13}\,\mathrm{n\,cm^{-2}}$ corresponds to a reactor stand-by interval.

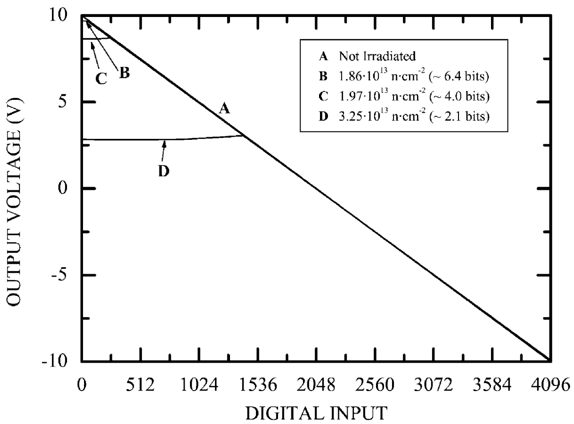

Fig. 8. Relationship between the digital input and the output of the DAC703KH converter. The input–output functions are similar when the input is at a high value and are significantly different for low range values.

it. However, most changes can be understood. Neutron irradiation leads to an increase of the semiconductor resistivity, decrease of the bipolar transistor gain, etc. [14]. Thus, DC errors and the relative number of bits must be modified by the variation of the internal elementary components and the subsequent change of the operating point of the internal networks of the devices.

The anomalous jump observed in AD667JN could not be understood since the information provided by the manufacturer was not enough. In contrast, the degradation of DAC703KH and the shape of its input–output function could be related to the damage suffered by the internal output operational amplifier. In fact, D/A converters with voltage output usually consist of a $R/2R$ ladder network, able to convert a digital input into current, and an additional integrated op amp to obtain a voltage output. We believe the observed behaviour is due to the inability of the internal output op amp to bias the resistor feedback network, as discussed in a previous work [13].

As pointed out in a previous section, shifts of line regulation coefficients are usual in irradiated voltage references, leading to the observed evolution of the integrated references. Also, the consumption decrease is usual in bipolar devices when irradiated with neutrons, such as the authors have reported for other devices [15] and it is corroborated by other results found in different public databases [16] or in the literature [17]. Finally, the deterioration of the frequency behaviour of op amps is a known phenomenon [14] and can explain the slower response of the converters with an internal output op amp (AD667, DAC703). In contrast, devices without an integrated op amp, such as the AD565, do not suffer a modification of the frequency response. Thus, the main advantage of current output D/A converters is that the operational amplifier can be selected from a set of rad-tol devices, eliminating the constriction of the use of an internal op amp whose radiation tolerance may not be good enough.

6. Rad-tolerant D/A converters

Among all the tested devices in the initial campaign, the most interesting was the AD565 from Analog Devices. The main reason behind this choice is that the internal reference voltage was the most affected parameter, while the other parameters were hardly affected. Thus, in order to harden the system, one only needs to replace the internal voltage reference by an external one. Besides, the external op amp needed by the DAC can be selected from those devices whose neutron tolerance has been established. Previous tests have shown a large tolerance for the OPA627, up to

$10^{14}\,n\,cm^{-2}$ without significant degradation [15], so this device was selected to be connected to the converter. In order to account for the tolerance of the whole "new" DAC, six samples were irradiated with external 10 V references but, unlike the preliminary tests, the op amps were placed on the same board as the converter.

As expected, the converter tolerated a neutron fluence of $5\times10^{13}\,n\,cm^{-2}$ and 2.1 kGy without significant degradation. Figs. 9 and 10 show the evolution of the main parameters (gain error, offset error and relative number of bits) of the devices irradiated to larger fluences. Neither the gain error nor the offset suffered a significant increase whereas the relative number of bits underwent a slight decrease. In any case its value was always higher than 11.

In short, the set of an AD565 plus an OPA627 op amp and an external reference is a satisfactory solution to be used in the LHC cryogenic system. The external reference voltage will be built by means of special rad-hard regulators developed at CERN [18], or with the output of a rad-hard ASIC, whose radiation tolerance has been proved in other neutron tests [3]. Nevertheless, the AD667JN and DAC703KH converters are recommended instead of the AD565AJD when the neutron fluence is lower than $10^{13}\,n\,cm^{-2}$ because of the larger accuracy and absence of external devices.

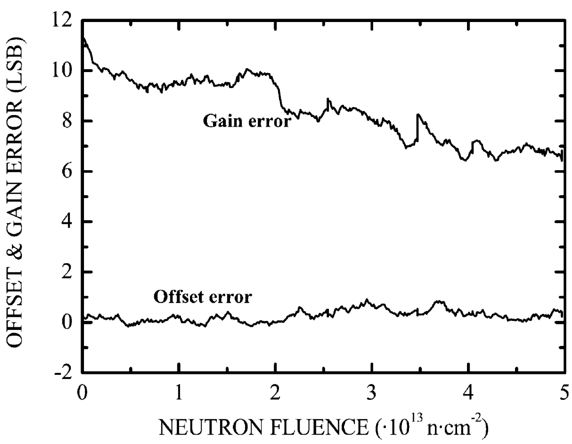

Fig. 9. Evolution of offset and gain error of irradiated AD565 with an external voltage reference.

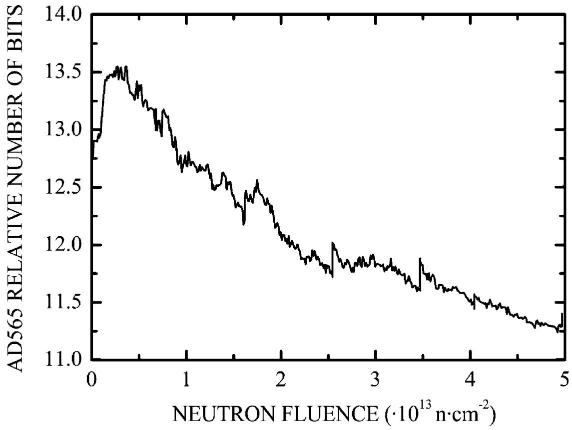

Fig. 10. Evolution of the relative number of bits, N_{REL}, of irradiated AD565 with an external voltage reference.

7. Conclusions

Electronics to be used in the LHC cryogenic system are expected to receive a significant radiation dose. Radiation tests are necessary in order to select the most suitable devices for the system. The problem of the selection of D/A converters has been solved after determining that the AD565 is able to tolerate the radiation levels forecasted for the LHC. The main handicap of this device is the large sensitivity of its internal voltage reference, which must be replaced by an external one. Finally, the op amp needed to convert the output current from current into voltage must also be radiation tolerant. We have proposed the use of OPA627 due to the extraordinary radiation tolerance observed in previous tests.

Accomplishing all these requirements, the tolerance of the D/A converter up to $5\times10^{13}\,n\,cm^{-2}$ and 2.1 kGy (Si) is guaranteed.

Acknowledgements

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