Radiation Tests on Commercial Instrumentation Amplifiers, Analog Switches & DAC's [a]

J. A. Agapito[1], N. P. Barradas[2], F. M. Cardeira[2], J. Casas[3], A. P. Fernandes[2], F. J. Franco[1], P. Gomes[3], I. C. Goncalves[2], A. H. Cachero[1], J. Lozano[1], J. G. Marques[2], A. Paz[1], M. J. Prata[2], A. J. G. Ramalho[2], M. A. Rodríguez Ruiz[3], J. P. Santos[1] and A. Vieira[2].

[1] Universidad Complutense (UCM), Electronics Dept., Madrid, Spain.
[2] Instituto Tecnológico e Nuclear (ITN), Sacavém, Portugal.
[3] CERN, LHC Division, Geneva, Switzerland.
agapito@fis.ucm.es

Abstract

A study of several commercial instrumentation amplifiers (INA110, INA111, INA114, INA116, INA118 & INA121) under neutron and vestigial gamma radiation was done. Some parameters (Gain, input offset voltage, input bias currents) were measured on-line and bandwidth, and slew rate were determined before and after radiation. The results of the testing of some voltage references REF102 and ADR290GR and the DG412 analog switch are shown. Finally, different digital-to-analog converters were tested under radiation.

I. INTRODUCTION

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 nominal power of 1 MW. The fluence of $5 \cdot 10^{13}$ n $\cdot$ cm^{-2} in the central PCB was reached in about 5 days, with 14 hours operation + 10 hours stand-by per day.

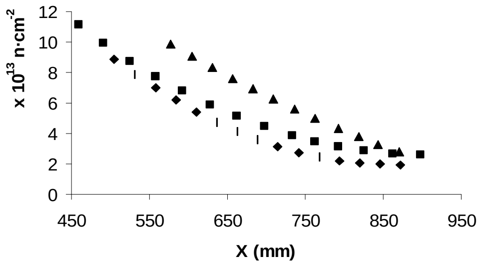

Figure 1: Fluence of neutrons 2.001

A 0.7 cm thick boral shield cut the thermal neutron component of the beam and a 4 cm thick Pb shield was used to reduce the total gamma dose below 2 kGy for the central PCB. The neutron fission fluxes were measured with 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 was also implemented.

Integration dosimeters placed on the back of first and last PCBs reveal, after completion of the tests, a total gamma dose in the 1.3 - 2.7 kGy range.

II. INSTRUMENTATION AMPLIFIERS

All irradiated instrumentation amplifiers are build in bipolar technology for the amplifying and output stages. The main difference between them is the input stage technology and the circuit topology, designed to confer the specific features of the device. Four samples of all devices were tested on line under neutron radiation.

The INA110KP is a monolithic FET-input instrumentation amplifier. Its current-feedback circuit topology and laser trimmed input stage provide excellent dynamic performance and accuracy. And the INA111AP is a high speed, FET-input instrumentation amplifier offering excellent performance. Both amplifiers have an extended bandwidth (450KHz at G=100).

The differential gain remains constant during the irradiation period until a total accumulated dose of neutrons of $1.25\text{-}1.5 \cdot 10^{13}$ n $\cdot$ cm^{-2}, 500 Gy is reached. A slight decrease of less than 1% (Figure 2) precedes to the dramatic drop off and the destruction of the amplifiers occurs when the total dose reaches $6\text{-}7 \cdot 10^{13}$ n $\cdot$ cm^{-2} (2.4kGy).

[a] This work has been financed by the co-operation agreement K476/LHC between CERN & UCM, by the Spanish research agency CICYT (TIC98-0737), and by the Portuguese research agency ICCTI.

There is no common behaviour for the input offset voltage. There is a high increment of this parameter for all devices. The highest measured value is 5.5 mV. However, no increment of the input bias currents was observed.

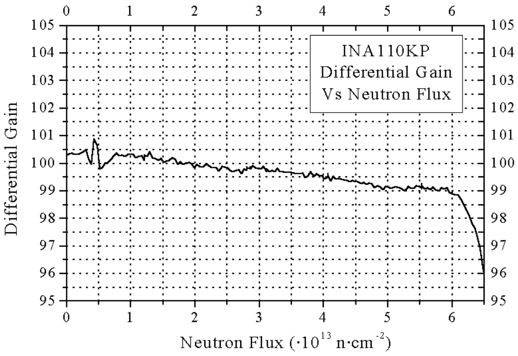

Figure 2: INA110. Differential. Gain

On the other hand, the bandwidth is reduced drastically, and the harmonic distortion increased, on both amplifiers (Table 1).

Table 1: INA110. Bandwidth and slew rate before and after radiation

Flux(n · cm^{-2})	B.W. MHz (G=10)	B.W. kHz (G=100)	S. R. V/μs
0	2.2	470	21
3.5 · 10^{13} 1.9kGy	1.55	200	6.2
5.1 · 10^{13} 2.2 kGy	1.2	130	4.8
6.8 · 10^{13} 2.4 kGy	0.83	62	3.0

The input-output dc voltage transfer characteristic was measured before and after irradiation (Figure 3). The voltage transfer characteristic was asymmetrically altered for all devices, and the positive and negative saturation voltages decreased.

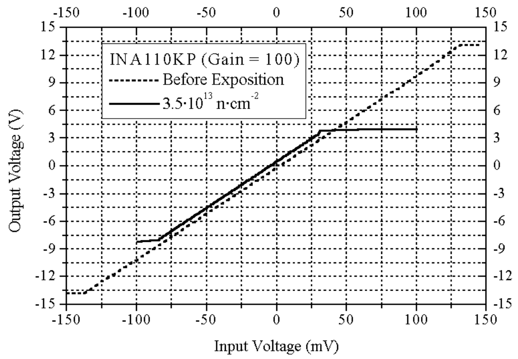

Figure 3: DC Voltage transfer for INA110 amplifier with ±15 V power supply

The INA121PA is a low power FET-input instrumentation amplifier, with a very low bias current and a smaller bandwidth than the former (50kHz G=100). The measured parameters were altered in a similar way to the precedents with the irradiation dose values reduced to a third. This can be related both to the smaller bandwidth and to the low power characteristics.

The INA114 is a low cost, general purpose bipolar instrumentation amplifier offering excellent accuracy. Two different models of the same amplifier were tested, AP & BG (plastic and ceramic package). The differential gain is constant until a total dose of 1.5 10^{13} - 1.8 · 10^{13} n · cm^{-2} (1kGy) is reached, and then it increases up to a 3% and is abruptly destroyed at 2.2 · 10^{13} - 2.8 · 10^{13} n · cm^{-2} (1.4kGy) (Figure 4).

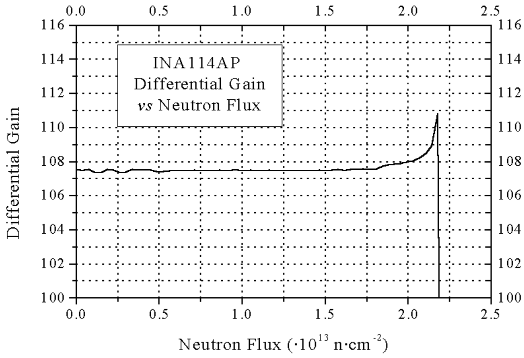

Figure 4: Diff. Gain bipolar Inst. Amp. (INA114)

An almost linear ratio between the input offset voltage and the accumulated total neutron dose is detected (Figure 5). The input bias currents increase slightly in all devices after irradiation.

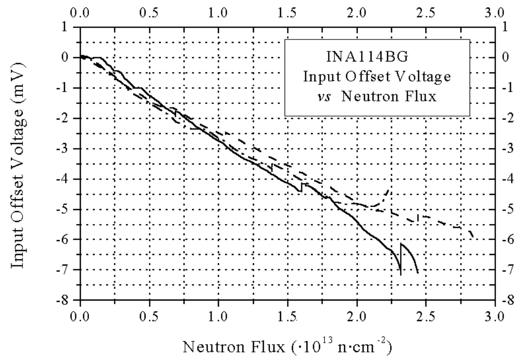

Figure 5: Input Offset Voltage vs. Neutron flux

A different behaviour of the two models was observed. The BG device revealed a higher tolerance to radiation, which can be attributed to the difference in the packages [1], and also that has lower values for bias currents and input offset voltage.

The INA118P is a bipolar low power, general purpose, instrumentation amplifier. Although their bandwidth is higher than that of INA114 these devices were destroyed earlier. The total neutron dose was 2 - 3 · 10^{12} cm^{-2} (200Gy). the input offset voltage increases up to 6 mV, and no variation in the input bias current has been detected.

The INA116PA is a complete monolithic

FET-input instrumentation amplifier with extremely low input bias current, DiFET inputs and special guarding techniques. It was quickly depredated, and were destroyed all devices with a total dose of $2 \cdot 10^{12}$ cm^{-2} (200Gy). Although DiFET operational amplifiers were revealed to be the best radiation tolerant devices [2], this can be attributed to the low bandwidth and micropower design technology of this device.

III. VOLTAGE REFERENCES

Several items of REF102BP and ADR290 voltage references were exposed to neutron radiation. A 15 V power supply was used for all devices, externally loaded to assure the 50% of the maximum current. The output voltage and the bias supply current for each device were measured on line. After irradiation the input-output DC transfer characteristic was determined for all surviving devices

A. REF102BP

REF102BP is a 10 V buried Zener diode voltage reference, from BURR-BROWN. The nominal output voltage error is less than ±0.05%, and the quiescent current is smaller than 1.4 mA with a maximum output current of 10 mA. Eight devices of two different fabrication series were irradiated with a total neutron dose between 2 and $9.9 \cdot 10^{13}$ $n \cdot cm^{-2}$ and a gamma residual total dose between 1400 and 2700 Gy.

Table 2: REF102BP. Minimum input voltage

Total Dose	Min. Input Voltage
0	10.8 V
$2.0 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.4kGy	10.8 V
$2.6 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.6kGy	12.6 V
$3.1 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.8kGy	17.0 V
$3.5 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.9kGy	13.1 V
$5.1 \cdot 10^{13}$ $n \cdot cm^{-2}$ 2.1kGy	19.9 V

The minimum voltage supply to get the nominal output of 10 V varies with the total accumulated dose as showed in Table 2

Table 3: REF102BP. Quiescent current

Total Dose	Quiesc. Current (mA)
0	1.30
$2.0 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.4kGy	0.90
$2.6 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.6kGy	0.94
$3.1 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.8kGy	0.75
$3.5 \cdot 10^{13}$ $n \cdot cm^{-2}$ 1.9kGy	0.88
$5.1 \cdot 10^{13}$ $n \cdot cm^{-2}$ 2.1kGy	0.55

The line regulation coefficient increased with radiation. For those items, that suffered a total neutron dose between 2.0 and $3.5 \cdot 10^{13}$ $n \cdot cm^{-2}$ (1.7 kGy), the value for the line regulation changed from 10 µV/V to between 10 and 20 mV/V. On the other hand, the quiescent current varied with the total neutron dose as shown in Table 3. All these parameters seem to be independent of the series production.

B. ADR290GR

The ADR290 is a 2.048 ± 0.006 V low noise, micropower precision voltage references that use an XFET (eXtra implanted junction FET) reference circuit. The new Analog Devices XFET architecture claims to offer significant performance improvements over traditional bandgap and Zener-based references.

Three samples were irradiated to a total neutron dose between 4.2 and $11 \cdot 10^{13}$ $n \cdot cm^{-2}$. All devices were destroyed at a value between 5 and $7 \cdot 10^{12}$ $n \cdot cm^{-2}$ (400Gy). Fig. 6 shows the behaviour of the output voltage with the radiation.

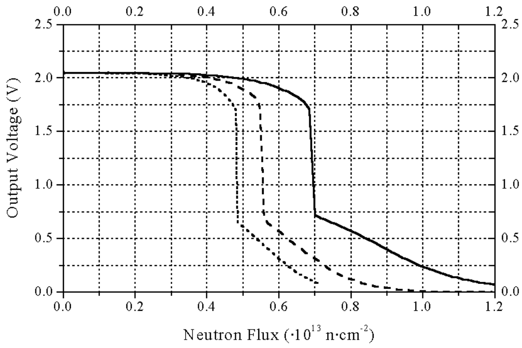

Figure 6: ADR290. Output Voltage vs. radiation

The output voltage exceeds the specification limits (± 6 mV) at a neutron dose between 2.5 and $3.5 \cdot 10^{12}$ $n \cdot cm^{-2}$, 200Gy. There is a small decrease of it in all samples, and then a hard drop off from 1.8 to 0.7 V. This is quite similar to other traditional voltage references as was previously reported (REF02) [3].

All the reported references use hard radiation tolerant devices as Zener diodes or JFET transistors as the first stage, and the amplifying and power stages built in bipolar technology. This suggests to be the cause of its degradation. Finally, the bias current decreases as the output voltage does

IV. ANALOG SWITCHES

DG412 is a four SPST normally open CMOS analog switches from MAXIM. It can operate with single or bipolar supply and is TTL/CMOS compatible. Three devices were exposed to a neutron radiation between 4.4 and $8.8 \cdot 10^{13}$ $n \cdot cm^{-2}$, and a residual gamma radiation about 2.000 - 2.700 Gy.

Analog switches are designed with two transistors in parallel, NMOS and PMOS, so that the equivalent resistance is almost constant for any voltage applied to their edges [4].

Measurements of the on resistance, the switching voltage and leakage currents with several bias supply's and logic levels were carried out on every device for the four switches before irradiation, and after the deactivation period (1 month later). During the deactivation period, these circuits remained unpolarized. The on resistances and the leakage currents were measured on line on the devices with a bias supply of ± 15 V and a logic level V_L = +5 V.

The on line measurements are shown on Figure 7.

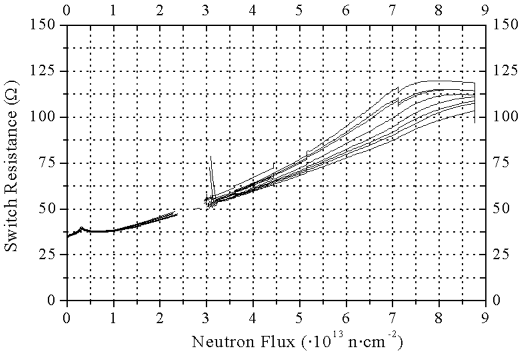

Figure 7: DG412. On resistance vs. radiation

The increase of the on resistance may be attributed either to the decrease of the mobility and concentration of carriers caused by neutrons or to the change in the threshold voltage of any of the MOS transistors. The latter effect (associated to the residual gamma radiation) could explain that the channel cannot be closed at the window between 2.25 and 3 · 10^{13} n · cm^{-2}, 700 and 900 Gy.

From the on line measurements a high increment of the leakage currents was detected, from nanoamps up to 2 mA. However, after the deactivation period a new measurement revealed that the leakage currents have disappeared. This may be associated to some annealing effect during the cooling period.

After irradiation the operating supply voltage V_+ - V_- need to be higher than a value between 11.9V and 13.4V, according to the radiation, and V_L = V_{CC}. This effect was not detected during the on line periods, and all switches were operating at V_{supply} = ± 15 V and V_L = 5 V. This latter degradation of CMOS devices took place during the cooling period after irradiation due to the movement of charges in dielectric materials.

For those devices still in operation the characteristic of resistance as a function of the input voltage was highly modified. Figure 8 shows this value for a ±10V supply voltage. For a higher supply voltage this anomalous value of the resistance with the input voltage decreases.

Since this characteristic is similar to that of a switch with a single operating MOS transistor (NMOS) [4], it can be assumed that the threshold voltage of the PMOS transistor has been strongly modified and consequently is always operating as an open circuit.

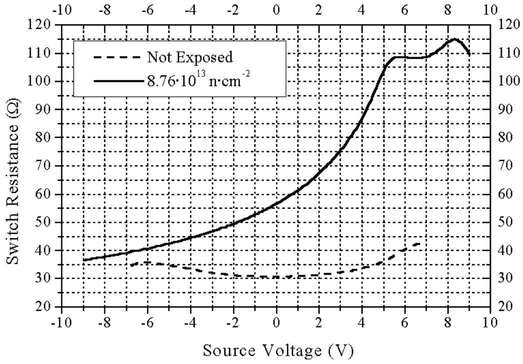

Figure 8: DG412. Resistance vs. Input voltage.

Furthermore, the switching voltage was measured, and Table 4 shows the switching level for a device that suffered a total dose of 8.8 · 10^{13} n · cm^{-2} and 2.7 kGy.

Table 4: DG412 Switching voltage (V_L = V_{CC}).

Supply	Before exp.	After exp.
Bipolar ±10 V	3.03 V	1.19 V
Bipolar ±15 V	4.08 V	2.72 V
Unipolar 0-15 V	4.24 V	2.71 V

V. DAC'S

Three different models were tested (AD565, AD667 and AD7541). The first two models were selected for their TTL technology, fast response and that were reported to tolerate up to 3 kGy, the first, and more than 2 · 10^{12} n · cm^{-2}, the second [5, 6]. The third model was selected for its CMOS technology.

On line output voltages measurements were carry out as the conversion to a digital sweep from zero to 4095. Neither offset nor gain correction were made. The neutron dose was between 3.1 and 3.4 · 10^{13} n · cm^{-2}, and gamma radiation about 1.8 kGy.

C. AD565AJD

The AD565A uses 12 precision, high-speed bipolar current-steering switches, control amplifier and a laser-trimmed thin-film resistor network to produce a very fast, high accuracy analog output current. The AD565A also includes a buried Zener reference comparable to the best discrete reference diodes. An external amplifier was implemented to provide a unipolar 0 to +10 volt output.

Four samples were tested in two different sessions. The offset error remains between 5 and 8 LSB. The gain error varies with the neutron radiation (Figure 9). A change lower than 5 LSB in the gain error is measured as the radiation increases from 0 up to $3.1 \cdot 10^{13}$ n · cm^{-2}, 1.8 kGy. Since then, the converter malfunctions. A day after the reactor stops it recovers and the obtained values are close to normal.

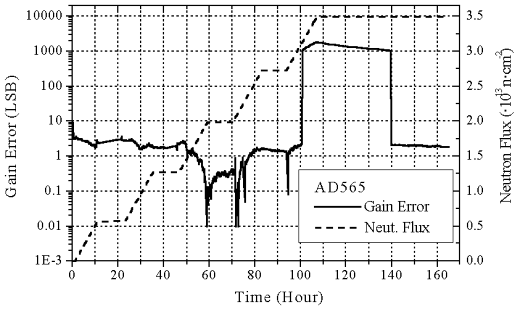

Figure 9: AD565 Gain error.

N_{EFF} remained during all the operation between 10.5 and 11 bits. Finally, the internal reference voltage varied 10 mV at the final radiation period. In one of the devices, there was an interval where the reference voltage decreased down to 7 V, but at the end recovered the nominal value.

D. AD667

The AD667 is a complete voltage output 12-bit digital-to-analog converter including a high stability buried Zener voltage reference and double-buffered input latch on a single chip. The converter uses 12 precision high speed bipolar current steering switches and a laser trimmed thin-film resistor network to provide fast settling time and high accuracy.

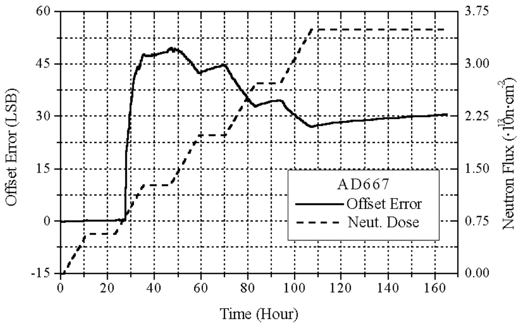

Figure 10: AD667. Offset error

Two samples were tested on line with radiation up to $3 \cdot 10^{13}$ n · cm^{-2}, 1.8 kGy. The initial offset error was less than 1.5 LSB but at a dose of $8 \cdot 10^{12}$ n · cm^{-2} (550Gy) increases abruptly up to 50 LSB at $1.2 \cdot 10^{13}$ n · cm^{-2} (720Gy). Then a decrease down to 30 LSB at maximum radiation point takes place (Figure 10). The gain error decreases from 15 down to 10 LSB, and the internal voltage reference increases 10 mV in 10 V at $3 \cdot 10^{13}$ n· cm^{-2}. N_{EFF} remain between 13 and 11 bits.

E. AD7541AKN & MX7541AKN

The AD7541A is a low cost, high performance 12-bit monolithic multiplying digital-to-analog converter. It is fabricated using advanced, low noise, thin film on CMOS technology. An external amplifier was implemented to provide a unipolar 0 to - 10 volt output.

One sample from Analog Devices and another from Maxim were tested on line with radiation up to $3 \cdot 10^{13}$ n · cm^{-2}, 1.8kGy. All of them were destroyed at $1.3 \cdot 10^{13}$ n · cm^{-2} (780Gy). It was reported that this converter could be destroyed at an accumulated gamma radiation dose of 100 Gy [6].

The offset and gain errors were constant until a dose $9 \cdot 10^{12}$ n · cm^{-2} (600Gy) was reached, then they increase until a total destruction. N_{EFF} was constant at 11 bits until $4 \cdot 10^{12}$ n · cm^{-2} (270Gy), and then decrease down to 7 bits at $1.1 \cdot 10^{13}$ n · cm^{-2} (800Gy) and then to 0 abruptly.

VI. Conclusions

Micropower design seems to decrease the radiation tolerance of instrumentation amplifiers. On the contrary, broad bandwidth and JFET inputs increase the radiation hardness.

The voltage reference REF102 can operate up to $5 \cdot 10^{13}$ n · cm^{-2} and 2.2 kGy.

Gamma radiation modifies strongly the characteristics of analog switches.

Some bipolar DAC's can operate without a significant degradation (E_{Off}<8LSB E_{Gain}<6 LSB) up to $3 \cdot 10^{13}$ n · cm^{-2} neutron flux and 1.8 kGy gamma radiation.

VII. References

[1] Adams, L *"Guidelines for the Use of Electronic Components in the Space Radiation Environment"*, http://www.estec.esa.nl/gpqwww/-paso/padocs/refer/uecsre/handbook.htm

[2] J. A. Agapito, et alt. "*Preliminary test for radiation tolerant electronic components for the LHC cryogenic system".* Proceedings. LEB99, Page 411-415.

[3] Agapito J. A., et alt. *"Instrumentation Amplifiers and Voltage Controlled Current Sources for LHC cryogenic Instrumentation"* Proceedings LEB2000, Page 275-279.

[4] "*How to select the Right CMOS Switch*" Tech. Art. from Maxim Integrated Products.

[5] Database of Electronics Radiation Response Information Centre http://erric.dasiac.com

[6] Database of NASA/GSFC Radiation Effects and Analysis http://flick.gsfc.nasa.gov