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RADIATION DAMAGE IN AMPLIFIERS USED FOR QUENCH DETECTION IN A SUPERCONDUCTING ACCELERATOR

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Abstract—The behaviour of some isolation amplifiers irradiated at the CERN PSAIF facility is described. These components were irradiated to total integrated neutron fluences varying from 1.2×10^{13} n/cm² ($E > 140$ keV) to 1.34×10^{14} n/cm² ($E > 140$ keV). The degradation of the electrical characteristics was measured versus doses. These amplifiers could be used for the superconducting magnet protection of LHC. They will be placed inside the tunnel and they will be exposed to 2.5×10^{13} n/cm² ($E > 140$ keV) during 10 year operation life time.

I. INTRODUCTION

CERN intends to build a particle accelerator (the Large Hadron Collider - LHC) using superconducting magnets. This machine will be installed in the tunnel of the existing Large Electron Positron (LEP) collider.

In the LHC many hundreds of large superconducting magnets will be powered in series to give the necessary bending power to maintain protons in their circular orbit. Such large superconducting magnets will run at the limit of existing technology in a high radiation environment.

Superconducting magnets are liable to loose their superconductivity or "quench" under fault conditions. The extremely high energy density of the LHC magnets could cause local overheating of the magnet in the section of the coil where the quench starts. To avoid this, the incipient quench must be detected as soon as possible. A signal must then be sent to fire strip heaters, which provoke quenching along the outer layer of the magnet coil. This spreads the energy out through a large volume of the winding, limiting the maximum temperature rise and maximum internal voltages [1]. Without the heaters the magnet could be destroyed by the local overheating.

The detection of quench is based on measurements of voltage between the ends of the two coils of each magnet. If a quench occurs, then a differential voltage appears and can be detected [2]. In order to trigger the protection system, these detection signals must be well above the noise level.

In addition to the quench detection amplifiers, a second set of amplifiers will continuously monitor the magnet voltages. When a fault occurs, the voltage wave form is recorded. This helps to localise and understand the origin of the quench and to identify "false" quenches [1, 2].

For transmitted signals the pick-up noise level is proportional to the length of the cable. Therefore, amplifiers which measure and amplify the voltages across the magnet must be situated in the tunnel near the magnet. Amplifiers must not only amplify the signals but also isolate the detection system from the magnet power circuit.

Electronic isolation amplifiers are clearly suitable for this requirements but they must be "radiation hard" to the levels given by LHC.

II. IRRADIATION AND DOSIMETRY

The dose in the LHC tunnel was estimated considering a proton beam of 8 TeV and taking into account the continuous losses due to the beam halo hitting the collimators and the vacuum chamber, the beam losses due to beam scattering and the accidental losses of the primary proton beam [3]. These calculations are made assuming continuous losses on the magnets of 10^6 protons per second, just below the alarm threshold of the beam loss monitoring system, for a year of operation (taken to be 10^7 seconds).

The dose and neutron fluences are given in Fig. 1 at various radial positions, from the beam centre to the tunnel walls for the nominal beam parameters and for the large majority of the magnets [4]. The neutron

Fig 1. Doses to LHC dipoles per year

fluences have been cut at 140 keV since displacement damage in semiconductors is negligible below that energy.

Systematic measurements at the existing CERN machines have shown that dose fluctuations of a factor ten are typical for proton accelerators, therefore the dose and fluence are expected to be 50 Gy and 2.5×10^{12} n/cm² (E>140 keV) per year at the tunnel wall where the amplifiers will be placed.

In order to investigate the influence of irradiation on the electrical characteristics of the amplifiers, the circuits have been submitted to preliminary radiation tests at the CERN PS-Acol Irradiation Facility (PSAIF). The irradiation area is sited behind the antiproton production target. During the production of antiprotons, this target is hit by a 26 GeV protons beam from the Proton Synchrotron (PS). At the irradiation place, a typical accelerator radiation field is then produced by the strong emission of secondary high-energy particles and neutrons. A container (18 cm in diameter and 20 cm in height) can be lowered along a tube to variable distance from the accelerator beam. The distance from the beam yields a variable dose rate. On-line measurements can be carried out in a safe radiation environment during the irradiation.

As described in [5], the dose inside the container has been measured as a function of the number of protons on the target.

Radiophotoluminescence (RPL) dosimeters, thermoluminescence dosimeters (TLD), polymer/alanine dosimeters (PAD) were used for dose measurements. Activation detectors and TLDs were used for neutron flux measurements and for evaluating the neutron spectrum by means of the LOUHI program [6]. The shape of the energy-spectrum of the neutrons, shown in Fig. 2, is given in n/cm² · s or in logarithmic energy bin Flux/BN/Log.

The values to be taken into account for the irradiation of our circuits are of 50 mGy (total dose mainly gammas) per pulse of 1.4×10^{13} protons and 1.1×10^9 n/cm² (E>140 keV) per pulse. According to the shape of the spectrum, the neutron fluence (E > 140 keV) is almost equivalent to the fluence at a 1 MeV equivalent dose. This was confirmed by measurements carried out with PIN diodes in 1993 [7].

TABLE I
LIST OF ALL EXPOSURES ON THE AMPLIFIERS

Exp. Nr.	Components Nr	Dose meas. [Gy]	Dose rate [Gy/hour]	Fluence [n/cm ²] E>140 KeV
1	AD289, ISO106, PWS727, DESY	500	5	1.10×10^{13}
2	AD289 (G=10)	3400	25	7.60×10^{13}
3	AD289 (G=30,90)	2000	25	4.50×10^{13}
4	AD210 (G=20)	6000	25	1.34×10^{14}

Table 1 shows the list of all radiation exposure levels and the dose rate on the amplifiers. The temperature during the irradiation was in the range between 18° and 25° C. With each set of components, some radiophotoluminescence dosimeters (RPL) were irradiated. The number of protons on the target was monitored to evaluate the absorbed dose all along the exposures. The degradation of the performance of the amplifiers was then measured as a function of the dose. Finally, the final dose was compared to the RPL readings at the end of each exposure.

Fig. 2. Neutron Spectrum in the PSAIF container

III. CHARACTERISTICS OF THE CIRCUITS TESTED

The electrical characteristics of the amplifiers required for our purpose are not specially severe: the quench detection level is between 0.1 and 0.5 V, the frequency response rates range from dc to a few kHz, the gain between 10 and 50, the voltage isolation between inputs and outputs is of the order of one thousand volts.

With a view to a complete isolation and protection from line transients, the following components have been chosen:

Isolation amplifiers: AD289J, AD210JN, ISO106
dc / dc converters: PWS727

Magnetic amplifier : made by DESY (Deutsches Elektronen-Synchrotron lab in Hamburg, Germany) for HERA (High Energy Ring Accelerator)

A. AD289J and AD210JN

Such amplifiers are a wide band, accurate, low-cost isolation amplifiers made by ANALOG DEVICES. These circuits are manufactured with surface-mounted components. They provide a complete isolation via a transformer coupling internal to the module. They are powered by a single + 15 V supply, and a ± 15 V isolated power is internally generated and supplied to both the input and output ports. This eliminates the need for an external DC/DC converter. They provide high accuracy with complete

galvanic insulation and protection from line transients or fault voltages.

The AD289J model offers a guaranteed gain non-linearity error of $\pm 0.05\%$, frequency response (-3 dB) from dc to 20 kHz and isolation between input and output of ± 2500 V.

The AD210JN model assures a maximum non-linearity of $\pm 0.025\%$, a bandwidth of 20 kHz (-3 dB) and isolation of 2500 V between any ports.

B. ISO106

This amplifier is a unity gain buffer isolation amplifier made by BURR BROWN intended for level input voltages on the order of 1V to 10 V. They may be preceded by amplifiers that precondition a low level signal and translate it to a high level. The amplifier isolates ± 10 V analogue signals by digitally encoding the input voltage and uniquely coupling across a differential ceramic capacitive barrier (3 pF).

The continuous isolation is rated for 3500 V rms; the typical frequency response varies from dc to 70 kHz; the non linearity gain is $\pm 0.04\%$ and the initial input offset voltage is in the range of ± 25 mV.

C. PWS727

The PWS727 is an isolated, unregulated dc/dc converter designed by BURR BROWN. It converts a single input voltage (10/18 Vdc) to bipolar voltages of the same value as the input. It provides a minimum isolation voltage of 1500 V rms, output currents of ± 15 mA at voltage accuracy of ± 0.75 V. This circuit could be used for powering an isolation amplifier without an integrated power supply, like the ISO106.

D. DESY Magnetic Amplifier

This is a low impedance passive device in which a current amplification is obtained by using non linear properties of ferromagnetic materials.

The ac circuit and the control circuit (Fig. 3) are magnetically coupled by means of a high permeability metal-glass core driven by a 200 Hz ac voltage [8]. When $E_c = 0$, the total voltage E_a applied to the ac circuit is shared between the resistive and the inductive charge. During the linear part of the magnetization curve, the inductance is high, the voltage drops across the resistance R is then small and the same is true for the current i_a . If the applied voltage (E_a) is such as to bring the circuit almost into the saturation zone the inductance falls. Most of voltage appears across the resistance R with a consequent high value for the current (I_a). The circuit behaviour is then non linear.

In operational conditions, the supply voltage E_a is adjusted so that its peak value just fails to saturate the magnetic core with $E_c = 0$. If an input voltage, ($E_c \neq 0$), is then applied to the control circuit, the corresponding current will change the flux in the core.

Also, as a consequence, the current (I_a) and the voltage across the resistance R will vary proportionally. The device is usually completed by ancillary equipment as a test winding (output 1-2 in Fig. 3). At the Hera machine a quench signal of ~ 100 mV is applied to the control circuit: the resulting current in the ac circuit produces a 10 V signal on R . The circuit behaviour is therefore strongly non linear: it can not be used as a monitoring amplifier (recording of data) but only as a threshold switch. It has been tested because it is expected to be radiation resistant. Moreover, it is cheap, reliable (no maintenance required), robust and has good voltage insulation. Its response in time is longer than 1 ms and its frequency response limited to ~ 100 Hz, and is thus suitable for our applications.

Fig. 3. Magnetic amplifier test circuit

IV. TESTING PROCEDURES

Tests were carried out on completed electronic circuits, mounted on a printed board and placed in the container in the irradiation area. All instrumentation needed to test and power the circuits was located outside the irradiation facility in a safe environment.

The electrical characteristics of each component were measured prior to the irradiation. During the exposures, all measurements were made in situ to take data without stopping the irradiation.

Parameters monitored were: power consumption, dc gain ($V_i = \pm 5$ V for ISO106, $V_i = \pm 0.5$ V for AD289, AD210), ac gain at 100 Hz, 1 KHz and 10 KHz ($V_i = 3 V_{peak}$ for ISO106, $V_i = 1 V_{peak}$ for AD289, AD210) and the offset voltage. An isolation test (1000 V_{rms} between input and output) was made at the beginning and at the end of the exposures on the ISO106, AD289 and AD210.

A batch of 2 samples of ISO106, PWS277, AD289J and one magnetic amplifier was subjected to the first radiation test. The total fluence of 1.1×10^{13} n/cm² ($E > 140$ keV) was obtained over a period of about one month. At the beginning of the experiment, the dose level was kept low to monitor any possible initial degradation of electrical characteristics. Dose levels were then progressively increased

and no appreciable changes were observed below a fluence of $2.9 \times 10^{12} \text{ n/cm}^2$ ($E > 140 \text{ keV}$).

The **second** exposure was performed to examine the behaviour of AD289J components in circuits with a gain of 10: the two samples previously irradiated were exposed to an additional fluence of $7.6 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$) during 13 days. The characteristics of the two AD289Js were checked before the new exposure test. The components did not show any change in performance. This fact excludes any **selfannealing** effect. Eight new components were added to the test series.

The AD289J were tested again in a **third** irradiation test to examine their behaviour at different gains of 30 and 90. Ten new amplifiers were assembled on printed circuit, in pairs, exactly as in the second test and exposed to a fluence of $4.5 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$) in 7 days.

Finally, during the **fourth** exposure, a batch of ten AD210JN amplifiers was exposed to a fluence of $1.34 \times 10^{14} \text{ n/cm}^2$ ($E > 140 \text{ keV}$) during 10 days.

V. ANALYSIS OF DATA

The behaviour of the **ISO106** amplifiers looks very good: the offset output can be considered constant as the dose is increased. The dc and ac gains did not change. The input current is almost stable up to the fluence of $2.9 \times 10^{12} \text{ n/cm}^2$ ($E > 140 \text{ keV}$) and then decreases by 10-20% at the fluence of $1.1 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$). Although the ISO106 isolation amplifier behaves better than the AD289J, it needs additional amplification and an external power supply. Therefore it was not considered for further experiments.

The dc/dc converters, **PWS727**, show a low resistance to radiation. The input current of the components strongly increases as the dose increases ($> 60\%$ for a fluence of $2.9 \times 10^{12} \text{ n/cm}^2$ ($E > 140 \text{ keV}$); the output voltages became noisy, unstable and for fluence larger than $2.9 \times 10^{12} \text{ n/cm}^2$ ($E > 140 \text{ keV}$), the components failed.

As expected the **magnetic amplifier** is radiation resistant. The circuit was optimised by adjusting the ac voltage (E_a) at 200 Hz to minimise the voltage across the resistor R. The optimum value was found for an ac voltage of $10 \text{ V}_{\text{rms}}$. Then, a signal of 0.5 V was applied to the control circuit and the resulting voltage was observed on R for different radiation doses (Fig. 3). Only a small dc drift was observed on the resistance R with an increase of the dose level. According to these results, the magnetic amplifier is the best choice for its insensitivity to radiation, making it a good level detector in a high radiation zone. However it has low input impedance and non linear gain.

The **AD289J** show good resistance to the radiation up to a fluence of $3.3 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$): small variations of the voltage offset (less than 10%), stable dc gain, and a stable gain at

100 Hz (gain of the circuit = 10). The power consumption decreased by about 40% with an increase of the radiation dose: but this variation does not seem to affect the performance of the circuit. On the other hand, the performance of the AD289J was more radiation sensitive at higher gain (Fig. 4): the characteristics deteriorated quickly already for a gain of 30. Their use in LHC is therefore limited to gains of 10.

Fig.4. A) AD289: test circuit

Fig. 4. B) AD289: dc gain vs. dose

Fig. 4. C) AD289: ac gain at 1 kHz

The **AD210JN** reacted the best under radiation. The electrical characteristics stay stable up to a fluence of $5.6 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$): only the power consumption decreased ($\sim 40\%$) with the radiation level, dc and ac gain and offset show no appreciable variation (Fig. 5).

In figures 4 and 5, the measurements of the electrical characteristics of every component have been

Fig. 5. A) AD210JN: test circuit

Fig. 5. B) AD210JN: Power consumption vs. dose

Fig. 5. C) AD210JN: dc gain ($G=20$) vs dose

normalised to 100 % for the original value prior to irradiation. The mean value of the samples has been drawn with the minimum/maximum deviations from the mean value for the different radiation doses.

VI. CONCLUSIONS

The isolation amplifiers **AD210JN** gave very promising results. They all operated adequately up to a fluence of $5.6 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$, which is equivalent to between 20 and 200 years of LHC running time, assuming a continuous loss of 10^6 protons per second on the magnets. The input offset remained less than 2 mV compared to quench detection levels between 0.2 to 0.5 V (still to be finally determined).

Moreover, the degradation of the circuits is gradual with the increase of the radiation dose. As a consequence, amplifiers can be monitored and eventually replaced if necessary during shut-down periods.

The current consumption decreases with the exposure, but the spread of values stay very narrow: $\pm 4 \text{ mA}$ prior to irradiation, $\pm 2 \text{ mA}$ at $5.6 \times 10^{13} \text{ n/cm}^2$ ($E > 140 \text{ keV}$). This property could be used to monitor the dose.

FUTURE DEVELOPMENTS

Ten new **AD210JN** will be tested in the tunnel of the Super Proton Synchrotron (SPS) at CERN at a total dose level of 500 Gy over 1 year. Such condition (a dose rate only 10 times stronger then in LHC) should reflect more closely the real situation.

Power consumption will be continuously monitored all over this test, in order to verify that the decrease in power consumption is strictly related to the dose received.

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