Radiation tolerant programmable power supply for the LHC beam screen heaters

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ABSTRACT: For the next LHC run, it is required to install 200 W of heating capacity per LHC beam screen heater to regenerate the beam screen by desorption of gas trapped on its walls. In the LHC, there are 272 beam screen heaters and the associated electronics limit presently the heating capacity to 25 W. Those electronics are, for the most part, installed inside the LHC tunnel and exposed to its radiation environment.

This paper describes the development of a new programmable power supply card that will be integrated into the existing LHC radiation tolerant electronic infrastructure used by the cryogenic system. Radiation tests were undertaken to qualify a power switch capable of coping with the 230 Vrms grid voltage and an analog signal multiplexer; these components are required respectively for satisfying the higher power requirements and for reducing the overall cost by using a single analog to digital converter to sample all the signals.

KEYWORDS: Radiation damage to electronic components; Radiation-hard electronics; Control and monitor systems online; Analogue electronic circuits

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1 Introduction

The LHC beam screen has different operation modes. During beam operation, it is used to prevent heat from reaching the beam pipe wall at 1.8 K and instead the heat is extracted by the beam screen that operates at a temperature between 5 and 20 K. The hydraulic circuit that cools the support posts of the LHC main magnets and the beam screen can reach up to about 100 m in length. Thermoacoustic induced oscillations [1] may be present resulting in a waste of cryogenic cooling power. Therefore the beam screen heater is used to exceed a critical temperature above which these oscillations are never present; in this mode up to 25 W of DC power is applied. During annual shutdowns the beam screen may be regenerated by increasing its temperature to 90 K; this requires 200 W to be dissipated on the beam screen electrical heater.

The cards presently installed are capable of applying power up to 25 W. Thus, the beam screen regeneration requires the development of a new programmable power supply card. The new card consolidates “weak” components and, when possible, reuses parts of the existing design that proved to operate reliably since 2008. Furthermore, it includes additional safety mechanisms and provides extensive feedback and diagnostics information.

The consolidated 2-channel card supports both DC (0–60 VDC, 0–2 A) and AC (50–400 VAC, 0–6 A) modes of operation. For the new AC mode, the card uses isolation transformers and power MOSFETs with Pulse Width Modulation (PWM) regulating power from the AC grid. For the selection of the radiation tolerant power MOSFETs, a radiation campaign took place at CERN’s CNRAD experimental area during 2012. CNRAD offers a mixed radiation field, similar to the one
expected in the LHC tunnel, which is produced by a 400 GeV proton beam hitting a nearby graphite target [2]. Three different commercial power MOSFETs were tested at CNRAD for a duration of approximately 6 months which corresponds to many years of LHC operation. The MOSFETs were tested both in passive (disconnected from AC) and active (230 V AC grid applied) modes. All three types of power MOSFETs survived the passive tests. The active tests were satisfied by only one MOSFET type; however it is not clear whether a thermal overrun or the radiation dose was responsible for the damage. The Total Integrated Dose (TID), equivalent neutrons (> 1 MeV) and fast hadrons (> 20 MeV) exceeded the radiation requirements for the power supply card. This is true for all 3 MOSFET types because during LHC irradiation (beam ON) the MOSFETs are in the passive mode.

The beam screen heater power cards provide measurements of the delivered current and voltage (for both AC and DC), of the temperature of the protection thermometer (either a thermocouple or a resistive sensor) and of some analog measurements that are used to correct any gain variation on the amplifiers or the ADC. In order to save cost and simplify the design, the use of analog switches was decided. For the design, three analog switch candidates were retained; two of them use a radiation-hard technology and one is a commercial part with a technology that could make it suitable for use in a radiation environment. The commercial switch was tested at both CNRAD and the Proton Irradiation Facility [3] of Paul Scherrer Institute (PSI) in Villigen, Switzerland. No failure was observed up to the maximum tested TID of 2'300 Gy-Si at PSI (230 MeV protons) and 340 Gy at CNRAD.

The new electronics power card is designed to safely operate in the LHC environment even in close proximity to the higher radiation regions of the dispersion-suppressors (DS) [4]. Annual doses for the DS regions are simulated in [5]. The highest expected dose is about 50 Gy/y (figure 18 of [5]). For the LHC arcs, where most of the cards will be installed, the annual doses are approximately 3 Gy/y (figure 3 of [6]). The paper presents the main functionalities of the programmable power supply and results of the radiation tests.

2 Basic design

The new programmable power supply card (figure 1) will be integrated into the existing electronic crates [7] as shown in figure 2a. Figure 2b describes the integration of the new card into the cryogenics electronics crate. The main functionalities of the crate are to provide the DC power through its “dc/ac supply card” to the Integrated Circuits (IC), to route through a “lateral fan in/out card” the protection thermometer and to provide communication to the WorldFIP communication interface via its “Communication Card”. The WorldFIP communication card transmits the data to the cryogenic controls infrastructure (cryogenic control, data storage and supervision for instrumentation specialists).

2.1 Protections

Several mechanisms are foreseen to protect the connected equipment and the card itself.

2.1.1 Safety relays

In standby conditions, the load is disconnected by electro-mechanical relays. Before enabling either the AC or DC mode, the correct contact operation of the relays is cross-checked by measuring the
connection/disconnection of a second contact which is mechanically coupled with the primary contact that handles the power supply terminals. The relays are of a “safety” type with forcibly guided contacts according to the EN 50205 type B. If a problem is detected, the card is set in standby conditions in order to protect the ICs from anomalous conditions.

### 2.1.2 Over-temperature protection

While applying power to the beam screen heater, its temperature is continuously monitored by the use of a thermocouple or a resistive sensor. When a protection threshold is exceeded, the card is disabled. Depending on its configuration, it is enabled either by an external command or automatically when proper operation conditions are retrieved.

For the thermocouple, several protection thresholds are foreseen (figure 3). A hardware threshold is set by positional switches on the card and is triggered when the temperature exceeds a predefined value. A reverse terminal connection of the thermocouple is protected by another hardware threshold; it is triggered when the thermocouple voltage goes below a minimum value which cannot normally be reached in a correctly installed thermocouple. Finally, a programmable threshold can also be set through the communication network.

### 2.1.3 Card level protections

The card is protected against thermal overruns by a thermal switch attached to its heatsink. Furthermore, it checks that the WorldFIP network is functional by tracking a special transmitted command that is continuously changed by a PC managing the WorldFIP network.
2.2 Design for radiation effects

A series of design steps were taken to guarantee proper operation in the radiation environment of the LHC. The power supplies are of the linear type, using the rad-hard regulators LHC4913 and LHC7913 from ST (+5 VDC, +2.5 VDC, ±1.25 VDC) and a toroidal transformer 70032K from Nuvotem Talema (±12 VDC). The anti-fuse FPGA is radiation-tolerant, its Flip-Flops (FF) are programmed in Triple-Module-Redundancy (TMR) and its state machines are encoded in “one-hot” and are “safe” [8]. The anti-fuse based FPGA is one-time-programmable by burning internal fuses to establish connections [9] and therefore its configuration is not affected by radiation. There are watchdogs to automatically reset the FPGA in case of abnormal operation; further external reset lines are available from the communication card. There are relays that can be driven directly by the communication card and perform a power cycle if a hard fault (e.g. latch-up) is detected. All analog signals are sampled in both straight and reverse polarity to remove offsets or drifts. There are also reference voltages to further correct gain errors. There are input pins with a fully combinational path (no FFs) that can safely disconnect the load even in the case of failure of the oscillator that drives the FPGA. All components that are used have been evaluated for use in the radiation environment of the LHC; they are presented later (see section 3).

2.3 Feedbacks-diagnostics

The voltage, current and heater temperature sensor data are transmitted for each of the two channels through the WorldFIP communication card. Additionally, extensive feedback status bits indicate whether the card is in a protected mode like over-temperature protection, relay malfunction, WorldFIP communication loss, reference voltage out of bounds or heatsink over-temperature. The status bits also provide the card configuration for the hardware protection thresholds, over-temperature sensor type selection, AC start-stop on AC Zero/Peak/Random setting and period of the AC power grid. The AC PWM can be configured to be switched at different values of the grid voltage: zero (to reduce noise pollution on the grid), maximum (for active loads) and random. Finally, a hardware diagnostics connector is located on the front panel of the card and it permits local access to 18 references/signals/supplies of the card.
3 Radiation qualification

The new card design uses IC components that have already been validated during the development of the radiation tolerant cards developed for the LHC cryogenic system [7, 10]. The main components retained are the Microsemi anti-fuse A54SX72A FPGA [11] that acts as a local controller, the Texas Instruments (TI) ADS7807UB ADC [12] using an external reference that samples all analog signals, the Analog Devices AD565AJRZ DAC [13] that is used to set the DC voltage level, the TI OPA541AM [14] power amplifier that feeds the DC power onto the external resistive load, the TI OPA627AU [15] operational amplifier which is used for filtering and amplification of signals, and the radiation hard Resistor and Pressure Bridge Front End R&PBFE ASIC (developed at CERN) used for the low level temperature signal conditioning. These Commercial Off-The-Shelf components (COTS) were validated several years ago and good radiation performance has been reported in the literature. However, a risk exists that an eventual change in the manufacturing process may degrade the radiation performance. To cope with this risk, samples of newly acquired components had to be re-evaluated. The OPA541AM and OPA627AU were re-qualified at PSI (see section 3.3) whereas the ADS7807UB parts are taken from the existing stock of LHC spare ICs.

3.1 AC power control

The AC power is applied by using a Pulse Width Modulation (PWM) algorithm with a typical period of 10 seconds that can be reduced to 5, 2.5 or 1.25 seconds. The galvanic insulation between the AC supply and the local IC supply is done by using a pulse transformer that transmits bursts of pulses that are rectified to produce a DC signal that turns on the power MOSFETs (figure 4).

Radiation tests were performed at CNRAD on both active (230V AC powered) and passive MOSFETs. The setup was controlled by a LabVIEW™ software which was sending the ON/OFF patterns and storing the data. The whole setup was remotely controlled through the internet in real time for the whole duration of the experiment which lasted 158 days (29 Jun 2012 to 03 Dec 2012).

The radiation was characterized by a Total Integrated Dose (TID) of 701.8 Gy (rate: 4.8 Gy/day), a hadron (> 20 MeV) fluence of $4.89 \times 10^{12}$ h/cm², and a neutron (> 1 MeV) fluence of 6.94 n/cm².

At the end of the test, all passive MOSFETs were operational. Only the FCA36N60NF MOSFET (table 1) survived the test in active mode. The failure mode for the other MOSFETs was not clear as the failure could be due to either radiation effects (gate rupture) or a thermal overrun. For safety reason when a failure occurred at a MOSFET of a pair, the power was removed from this pair; consequently the second MOSFET remained disconnected from the AC grid. A few of those MOSFETs were found to be operational having a non-zero gate control current (μA range).

The main radiation effect is a shift of the turn-on gate threshold voltage (figure 5) that depends on whether the MOSFET was irradiated in the passive or active mode.

3.2 Switch for analog signal multiplexing

The card design relies on the use of analog switches to use a single ADC and thus greatly reduce its cost. Suitable rad-hard analog switches were available from two vendors. However, the low-cost
Figure 4. Simplified diagram of the setup used for radiation test of the power MOSFETs. 12 MOSFET pairs were tested in total (one pair shown in the figure).

| MOSFET       | Manufacturer          | Breakdown Voltage | Drain Current | ON Resistance | Heatsink Required | Test | Test |
|--------------|------------------------|-------------------|---------------|---------------|------------------|------|------|
| FCA36N60NF   | Fairchild              | 600 V             | 34.9 A        | 0.095 Ω       | No               | OK   | OK   |
| FDP7N60NZ    | Fairchild              | 600 V             | 6.5 A         | 1.25 Ω        | Yes              | OK   | ?    |
| STFI10NK60Z  | STMicroelectronics      | 600 V             | 10 A          | 0.65 Ω        | Yes              | OK   | ?    |

commercial IC SW06GSZ [16] (Quad SPST JFET Analog Switch) from Analog Devices looked like a good candidate for a radiation tolerant COTS part and it was then tested in PSI.

The analog switches were initially tested at CNRAD by using part of the cabling used for the MOSFETs test (figure 4). There were 6 switches kept in a plastic bag and 18 switches (72 channels) powered with ±12 VDC and grouped in 3 groups of 6 switches. After an irradiation dose of 50 Gy, the control input current had increased in such an extent that the experimental set-up was not adequate to drive ON/OFF multiple channels in parallel. The active high channels (Ch1&2) remained constantly ON and the active low channels (Ch3&4) remained constantly OFF. The switches were nevertheless kept under power until the end of the experiment reaching a dose of 347.5 Gy (rate: 4.8 Gy/day), hadron (> 20 MeV) fluence of $2.42 \times 10^{12}$ h/cm² and neutron (>1 MeV) fluence of 3.44 n/cm². At the end of the radiation campaign all switches were functional when tested in the laboratory.

A new test was performed at the PSI (Villigen, Switzerland) on the 24th FEB 2013; it revealed very good radiation performance and no failures were observed for the 10 tested ICs up to the maximum level of 2’300 Gy (rate: 360 Gy/h) and 230 MeV proton fluence of $4.3 \times 10^{12}$ p/cm². The new test set-up (figure 6) was designed to be able to measure variations in the input control threshold voltage ($V_{\text{INL}}$, $V_{\text{INH}}$) by applying sinusoidal commands, logic control input current ($I_{\text{INL}}$, $I_{\text{INH}}$), leakage currents in input and output connections ($I_{S(\text{OFF})}$, $I_{D(\text{OFF})}$), power supply currents ($I_+$, $I_-$),
Figure 5. MOSFET output current versus gate voltage. Passive tests were performed for 30 devices of each type. Their characteristics were measured before irradiation (0 Gy), 10 samples were removed from CNRAD after 353 Gy and the rest at 702 Gy. (a) passive (unpowered) and (b) active (connected to 230 V AC) data for FCA36N60NF. Passive data for (c) STFI10NK60Z and (d) FCA36N60NF.

Figure 6. Simplified diagram of the test setup used for the irradiation test of the SW06GSZ analog switch. Only the switch was irradiated. For clarity reasons only 1 of the 10 analog switches is shown in this diagram.

The radiation provokes a slight variation of the ON resistance and of the supply currents (figure 7) and a proportionally larger variation of the logic control input current. Those variations were taken into consideration during the design phase of the circuit.
Figure 7. The current consumption of the positive (a) and negative (b) supply normalized per IC (measured in groups); round: ICs 1-2, square: ICs 3-6, triangle: ICs 7-10. c) The leakage current of the control input pins $I_{\text{INL}}$ grouped in 20 channels measured at $V_{\text{INL}}=0$; square: 20 logic inputs (Ch1&3), round: 20 logic inputs (Ch2&4). d) The $R_{\text{ON}}$ resistance of the 40 switch channels before irradiation (round) and at 1000 Gy (square) and the variation % per channel (triangle).

Figure 8. a) Summed current consumption for 2xOPA541AM. b) DC current gain for the 2N6388G.

3.3 Ancillary components

COTS are used to set reference voltages, provide amplification, low pass and low leakage filtering, clock to the FPGA, etc. These components are expected to operate without any major issue in the LHC environment. However, a qualitative measurement of the drift in their characteristics with respect to radiation was performed up to 1000 Gy (table 2). All components are compatible with the requirements with the only exception being the darlington transistor (figure 8) that is used exclusively when the card is installed in protected radiation-free areas. The irradiation took place at PSI on the 20–21 JUL 2013 using a 230 MeV p+ beam.
Table 2. Radiation results of ancillary components.

| Type                  | Component                  | Manufacturer   | Purpose       | Result |
|-----------------------|----------------------------|----------------|---------------|--------|
| Power Op Amp          | OPA541AM                   | Texas Inst.    | Re-qualify    | Drift  |
| Op Amp                | OPA627AU                   | Texas Inst.    | Re-qualify    | OK     |
| Osc 10MHz, 5V         | LFSPXO017735               | IQD            | NEW           | OK     |
| Osc 10MHz, 5V         | CSX750FCC10.000M-UT        | Citizen Fin.   | NEW           | OK     |
| High-gain transistor  | 2N6388G                    | ON Semi.       | NEW           | Drift  |
| Zener diodes          | BZX84B5V6 & BZX84A2V4      | NXP Semi.      | NEW           | OK     |
| Zener diodes          | 1N5333BG & 1N5350BG        | ON Semi.       | NEW           | OK     |
| 82uF polyester        | B32526T0826K               | EPCOS          | NEW           | OK     |
| 10uF polypropylene    | MKP1848S61050JP2C          | VISHAY         | NEW           | OK     |
| 47nF X1 polyprop.     | BFC233810473               | VISHAY         | NEW           | OK     |
| Diode                 | PMLL4448.115               | NXP Semi.      | NEW           | OK     |
| Schottky diodes       | VS-10BQ100 & VS-30BQ100    | VISHAY         | NEW           | OK     |

4 Conclusion

All of the functionalities of the new radiation tolerant programmable supply card have been verified in the laboratory and through radiation tests on independent ICs. That gives confidence of an overall radiation tolerance that shall permit to install the cards in all LHC areas.

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