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DEVELOPMENT AND CHARACTERIZATION OF A RADIATION-TOLERANT POWER SUPPLY FOR BEAM INSTRUMENTATION

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Abstract

CERN's Beam Instrumentation Group is developing a mini-crate to host the future Beam Loss Monitor (BLM) and Beam Positioning Monitor (BPM) systems acquisition electronics at HL-LHC and SPS accelerators. For this purpose, a new power supply has been designed to meet the low noise requirements, high reliability, and availability standards for these harsh radioactive environments. This design makes use of CERN-developed ASICs and radiation-tolerant qualified COTS and follows a modular architecture for quick interventions and safe handling. The paper presents the design, prototype characterisation results, identified issues, and mitigation methods to achieve the required radiation tolerance.

INTRODUCTION

CERN's Large Hadron Collider (LHC) Beam Loss Monitoring system [1-3] is a critical system for the protection of the particle accelerator and is extensively used to optimise and crosscheck several other instruments and beam processes. An upgrade of the electronics stack is planned for the Hi-Lumi project's changes in the Inner Triplet areas of IP1 & 5 and at the complete SPS ring during the Long Shutdown (LS3). Once the performance of the new electronics is validated at those regions, the same system will be installed also in the LHC accelerator during LS4 for monitoring a total of about 4000 ionisation chamber type detectors.

Given the system's scale in terms of electronics and detectors, it is essential to design a tunnel acquisition mini-crate capable of withstanding radiation doses up to 1 kGy. The crate must reliably supply low-noise power to the sensitive front-end analogue circuits while remaining resilient to short circuits and robust to enable all types of interventions.

MINI-CRATE DESIGN

To meet the requirements mentioned before, it was decided to choose an architecture in which the voltage conversion takes place by means of two independent modules: Input Power Unit (BLEIPU) and Power Supply Unit (BLEPSU). The BLEIPU is used to transform the 230 VAC input into different AC voltage buses that are filtered, monitored, protected, and finally sent to the BLEPSU via a passive backplane. Then the BLEPSU is used to produce different DC voltages needed by the acquisition electronics. The voltage buses provided are as follows: +5 VDC; -5 VDC; +2.5 VDC and +1.2 VDC, where the +5 VDC; -5 VDC are dedicated to supplying the "analogue" circuitry, while the +2.5 VDC and +1.2 VDC supply the "digital" circuitry of the acquisition board. In addition, the BLEPSU also includes the 1500 VDC detector bias voltage conversion function, supplied by the surface rack to the whole detectors chain, to adapt such voltage to a level compatible with the monitoring function, which is mandatory to ensure the reliability of the entire detector installation.

All voltages present on the backplane are monitored by a control unit (BLEACCM) which offers the possibility of remotely restarting both the 'analogue' and 'digital' power buses. Also available through a front panel connector is the possibility to plug a diagnostic tool module.

The architecture maintains full backwards compatibility with the current LHC system electronics, so parts could be swapped, which is the preferred approach to upgrade an existing system classified with Safety and Integrity Level 3 (SIL3), and to provide high flexibility during the development and testing phases.

Figure 1 shows the prototype of the mini-crate where the BLEIPU and BLEPSU modules are tested with the current BLM electronics installed at the LHC.

Figure 1: Mini-crate overview.

Input Power Unit (BLEIPU)

The BLEIPU core component is a custom toroidal transformer, with a diameter of 83 mm and a height of 50 mm which delivers a global output power of about 90 Watts. The output stage consists of three independent windings (WDG) which are distributed as summarised in Table 1.

Table 1: Winding Outputs

WDG	Output Voltage	Output Current
1	8.0 V	7.87 A
2	8.0 V	2.00 A
3	9.3 V	1.39 A

Materials chosen for radiation resistance and compatibility with the CERN facility installations are Steel Tape for the core, PET film (mylar A) for the insulation layers, and braided fiberglass coated with a modified polyvinyl chloride resin for the sleeve.

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The transformer Windings #1 is the source of the generation of the positive voltage rails: +5 VDC; +2.5 VDC and +1.2 VDC; the transformer Winding #2 is used for the negative voltage rail -5 VDC; the transformer Winding #3 is dedicated to the generation of all auxiliary diagnostic functions which, as basic principle of high reliability design, must be separated from the main power function.

Figure 2 shows the Input Power Unit, where on the left side is located the power entry module which allows the connection of the main power to the mini-rack, and offers a power outlet if needed for inspection and interventions through a laptop. Next to the power socket is placed the AC filter and on top the main fuse holder. The image in Fig. 2 was obtained by opening the metal box that protects the electronic unit from shock, mishandling and transport in the backpack during maintenance and repair operations.

The design incorporates a pair of voltage rectifiers positioned between the transformer and the backplane interface connector, providing the capability to monitor and diagnose the operational state of windings #1 and #2.

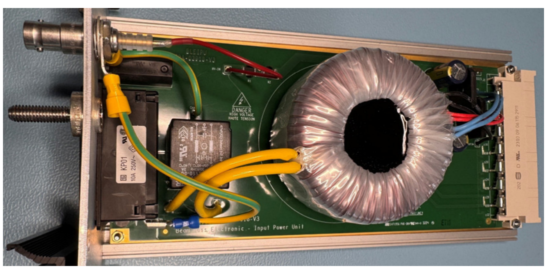

Figure 2: Input Power Unit.

Power Supply Unit (BLEPSU)

The BLEPSU receives the voltages generated across winding #1 and winding #2 inside the BLEIPU module and performs voltage rectification through diode bridges cooled by a custom common heat sink that is intended to keep the junction-ambient thermal resistance below 18 °C/W. The mechanical and thermal coupling between the body of the rectifiers and the heat sink is guaranteed by means of a thermally conductive gap filling material.

Therefore, as shown in the schematic in Fig. 3, in the worst condition, which occurs if the inputs of CERN DC/DC converters named bPOL12Vs [4] and used to generate +2.5 VDC and +1.2 VDC have an input overcurrent and the fuses have not yet tripped, the maximum junction temperature remains below 23 °C above the temperature ambient. This indicates that the rectifier can safely operate under this condition, even if the ambient temperature reaches 100 °C. Two rectifiers are used in the design, the first serving the circuitry to generate the +2.5 VDC and +1.2 VDC, considered as "digital" supply voltages, and the second to generate the +5 VDC, considered as "analogue" supply voltages. This solution has the advantage of globally reducing ground-conducted noise for the analogue circuits powered by the BLEPSU module. The "ENABLE_DIGITAL" and "ENABLE_ANALOG" signals are used to independently power reboot analogue and digital voltage buses. Under all nominal conditions they are not operational, and the mini-crate automatically turns ON as soon as the main power is supplied to the input power connector.

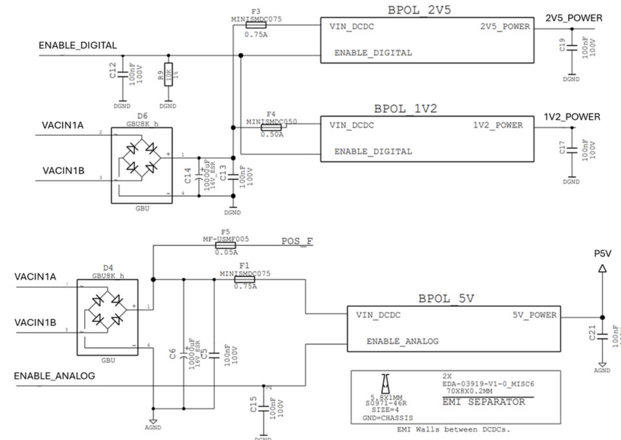

Figure 3: Positive voltage rail block diagram.

The bPOL12Vs [5] are high radiation tolerant DC/DC converters developed by CERN and able to deliver an output power of 10 W. They are used to generate +5 VDC, +2.5 VDC and +1.2 VDC, and their cooling is guaranteed by means of three independent heat sinks based on the same method used for the diode bridges.

Since the bPOL12V was originally designed to generate output voltages up to +3.3 VDC, and the mini-crate required a +5 VDC rail, a workaround was implemented to adjust the DC/DC feedback loop. As shown in Fig. 4, resistors R10 and R11 divide the output voltage by a factor of two, so that the feedback input receives +2.5 V. This ensures that the voltage at the feedback input remains within the specifications of the bPOL12V.

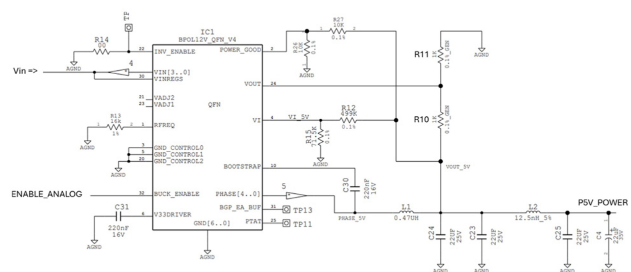

Figure 4: bPOL12V @ +5 VDC output.

Unlike the reference design of the bPOL12V [4], the air-core inductor was replaced by an industrial shielded inductor. Since the bPOL12V was developed primarily for typical use within the LHC experiments, where there is a strong magnetic field, and not having the same constraint, the choice of an industrial shielded inductor offered the advantage of 40 times lower series resistance. This solution brought significant efficiency benefits when delivering a high current, e.g. a 10 % efficiency gain at 4 A.

The generation of the -5 VDC cannot be done through the bPOL12V device and an alternative solution based on the radiation qualification of the MC7905ACD2 linear voltage regulator was proposed.

The circuit shown in Fig. 5 shows the rectification represented by the group consisting of D5, C8 and C9, the

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overcurrent protection by the resettable fuse F2, the power restart option achieved by the group consisting of C7, R8, T3, RL2 and D3, and finally the linear voltage regulator equipped with input and output filters and protections.
Since the linear regulator lacks an ON/OFF control pin, relay RL2 is employed to cycle the -5 VDC voltage bus using the same signal that controls the power cycle of the +5 VDC bus.

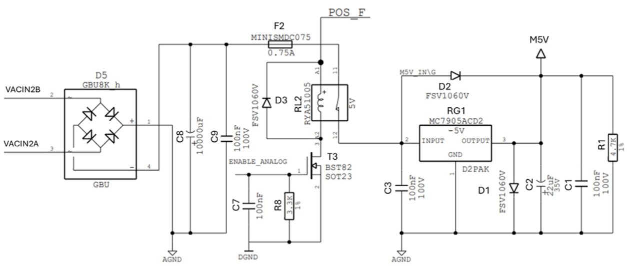

Figure 5: Negative voltage rail schematics.

Figure 6 shows the internal assembly of the power supply with the voltage rectifiers on the right side of the picture, based on ultra-low ESR 10 mF aluminium electrolytic capacitors.

More centrally, one can see the three black-colour heatsinks assigned to the three bPOL12Vs on the board, as well as the heatsink on the top side of the linear voltage regulator, which is also equipped with a second heatsink on the bottom side. The left side of the circuit board houses all the filtering and protection components of the linear voltage regulator and the status LEDs that allow the presence of the +5 VCC, -5 VCC, +2.5 VCC and +1.2 VCC voltage rails to be displayed on the front panel.

Cooling of the power supply system, achieved both by forced convection and by conduction through the metal structure and an integrated chassis layer on the circuit board, is a key aspect of the design. This is necessary because the mini-crate must withstand short circuits and overcurrent, conditions that entail long waiting periods before access to the CERN tunnels is allowed for inspection and repair.

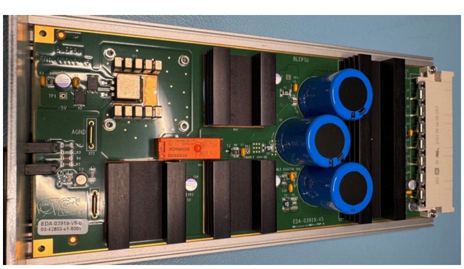
Figure 6: Power Supply Unit.

Controller Card (BLEACCM)

The mini-crate's control board BLEACCM, designed to be single-fault tolerant and fail-safe, handles diagnostics of all power supply rails (AC and DC), offers the ability to independently restart analogue and digital voltage rails It also provides the connection of a hand-held tester device which can be attached to the front panel for an automatic test capability currently under development, including corrective actions recommendation to the operator.

DESIGN VALIDATION

The validation of the design was carried out through several steps to verify and ensure the robustness of the design under all possible conditions in which the mini-crate will be exposed.

The performance tests were carried out using a climatic chamber capable of reproducing the temperature and humidity conditions expected in the real application, which are assumed to range from 5 °C and 50 °C for temperature and 20 % to 70 % for humidity.

A total of ten verification steps were performed as listed below [6]:

1. Easy access for assembly, maintenance and robustness of the mini-crate.
2. Backward compatibility with the current LHC system.
3. BLEPSU power-up-time of each power rail.
4. BLEPSU efficiency for each DC/DC module.
5. BLEPSU output voltage ripple.
6. Thermal dissipation in worst case (forced ventilation fault) to verify the redundant power dissipation system.
7. Permanent short circuit resistance and recovery.
8. Slow overcurrent protection and recovery.
9. Stress test in environmental temperature up to 100 °C.
10. Radiation tests for a Total Ionizing Dose >1 kGy.

CONCLUSION

The mini-crate successfully passed all validation tests and proved to be very robust and suitable for the CERN tunnel applications. A total of 60 crates will be manufactured and installed to upgrade the SPS BLM system, and once their operational performance is validated, the same system will be deployed to upgrade the LHC BLM system.

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