Article

A Burn-in test station for the ATLAS Phase-II Tile-calorimeter low-voltage power supply transformer-coupled buck converters

Ryan Mckenzie, on behalf of the ATLAS Tile Calorimeter System [1,†] 0000-0001-9618-3689

[1] School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa.

* Correspondence: ryan.peter.mckenzie@cern.ch;

Abstract: The upgrade of the ATLAS hadronic tile-calorimeter (TileCal) Low-Voltage Power Supply (LVPS) falls under the high-luminosity LHC upgrade project. This article serves to provide an overview of the development of a Burn-in test station for an upgraded LVPS component known as a Brick. These Bricks are radiation hard transformer-coupled buck converters that function to step-down bulk 200 V DC power to the 10 V DC power required by the on-detector electronics. To ensure the high reliability of the Bricks, once installed within the TileCal, a Burn-in test station has been designed and built. The Burn-in procedure subjects the Bricks to sub-optimal operating conditions that function to accelerate their aging as well as to stimulate failure mechanisms. This results in elements of the Brick that would fail prematurely within the TileCal failing within the Burn-in station or to experience performance degradation that can be detected by followup testing effectively screening out the 'weak' sub-population effectively increasing the reliability of the remaining population of Bricks. The Burn-in station is of a fully custom design in both its hardware and software. The development of the test station will be explored in detail and the preliminary burn-in procedure to be employed will be presented finally culminating in a discussion of preliminary burn-in results.

Keywords: ATLAS; Tilecal; Phase-II upgrade; Quality assurance testing; Burn-in; Transformer-Coupled Buck Converters

Citation: Mckenzie, R. A Burn-in test station for the ATLAS Phase-II Tile-calorimeter low-voltage power supply transformer-coupled buck converters . *Journal Not Specified* **2022**, *1*, 0. https://doi.org/

Received:
Accepted:
Published:

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1. Introduction

The TileCal is a sampling calorimeter that forms the central barrel region of the Hadronic calorimeter of the ATLAS (A Toroidal LHC ApparatuS) experiment at the Large Hadron Collider (LHC) [1]. It performs several critical functions within ATLAS such the identification of hadronic jets and measurement of their energy and direction. It also participates in the measurement of the missing transverse momentum carried by non-interacting particles, muon identification, and provides inputs to the Level-1 calorimeter trigger system. The detector is located in the pseudorapidity region $|\eta| < 1.7$ [1] and is partitioned into 3 barrel regions. The Long-Barrel (LB) region is centrally located with the Extended Barrel (EB) regions located on opposing sides of the long-barrel as seen in Figure 1. Each barrel region consists of 64 wedge shaped modules which cover $\triangle\phi \sim 0.1$.[1] The on-detector electronics are housed within drawers located on the outer radii of the Tilecal and receive low-voltage power from Low-Voltage Power Supplies (LVPS) located in adjacent shielded boxes referred to as Fingers. The LB Modules are serviced by 2 LVPS while the EB modules are serviced by only 1 adding to a total of 256 LVPS within the

[1] ATLAS makes use of a right-handed coordinate system with its origin located at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r,ϕ) are used in the transverse plane, where ϕ is defined as the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -ln \tan(\theta/2)$.

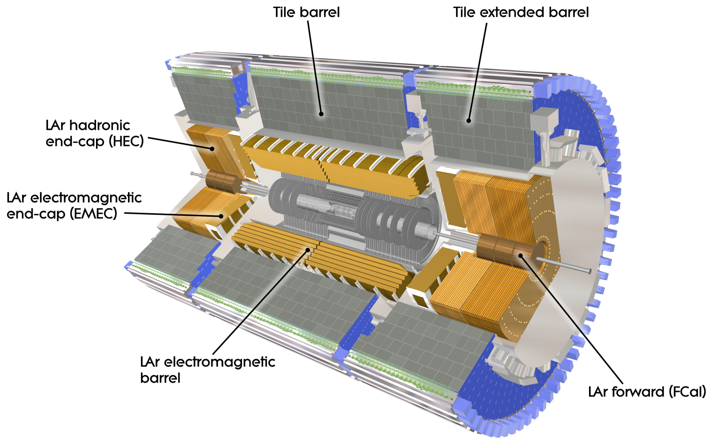

Figure 1. Computer Generated image of the ATLAS calorimeter [2]. The LVPS Fingers are illustrated as blue boxes located on the outer radii of the ATLAS inner barrel.

Tilecal. Each LVPS contains eight transformer-coupled buck converters (Bricks), a fuse-board, an Embedded-Local Monitoring Board (ELMB) motherboard, a wiring harness, and a water-cooled heat sink to which the Bricks are affixed.

In the first quarter of 2029 the start of the operation of the High Luminosity LHC is planned [3]. The resulting environment has necessitated the development of new electronics, both on- and off-detector, to ensure the continued peak performance of the Tilecal. The development, production, installation and commissioning of the new electronics falls under the Tilecal Phase-II upgrade [4–6]. The Tilecal Low-Voltage Power Supplies (LVPS) and the components therein contained will be upgraded as part of Phase-II upgrade.

Access to the LVPS Bricks is of the order of once per year due to their location within the detector. Therefore, any Bricks that experience a failure[2] will result in a portion of the module to which they provide power being offline for a commensurate period of time with the inability to collect collision data. Due to this, the reliability of the Bricks is of the utmost importance. A reliability study has been conducted and a robust quality assurance procedure, that is to be applied to every Brick post-production, has been developed. The quality assurance procedure is partitioned into five distinct tests, namely an automated visual inspection, x-ray scan, initial testing, burn-in and final testing. Each test plays a specific role in ensuring the high reliability of the Brick population once installed on-detector. Burn-in testing and its associated apparatus forms the crux of this article and will be covered in detail from section 3 onwards.

2. Phase-II Upgrade LVPS Brick

The LVPS Bricks are of an iterative design with the V6.5.4 being the first to be installed within the TileCal in 2007. Although these Bricks generally functioned well they began to exhibit a sensitivity to trip at a rate that scaled with the luminosity of the beam. To address this issue as well as implement design changes motivated by experience with the V6.5.4 Bricks the V7 Bricks were designed with the V7.5.0 Bricks being installed within the TileCal in 2013. The V7.5.0 Bricks are to remain within the TileCal up until the TileCal Phase-II upgrade at which point they will be replaced with the V8 Bricks. The replacement of the V7.5.0 Bricks was motivated due to several key factors such the increased radiation hardness requirements of active components necessitated by the high luminosity environment, the introduction of a third stage to the low-voltage power distribution system of the TileCal

[2] A failure is defined as the permanent inability of the LVPS to provide power to its associated front-end electronics therefore requiring replacement.

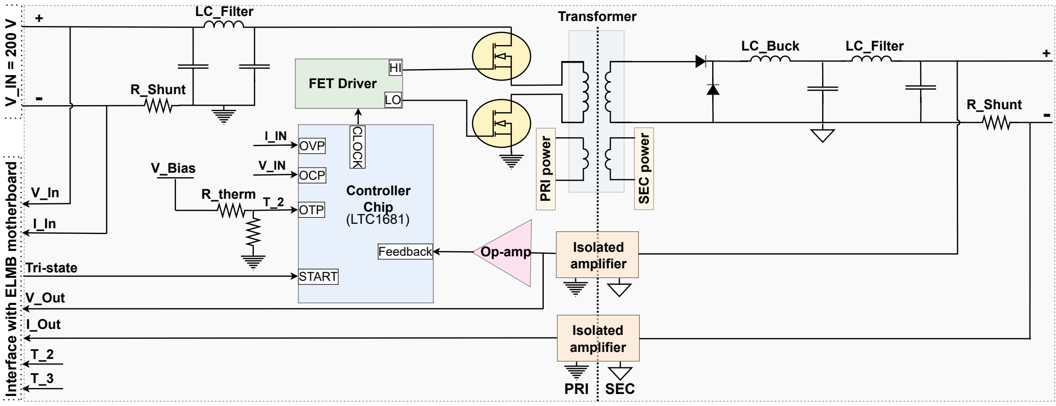

Figure 2. Functional block diagram of an LVPS Brick.

allowing for a single Brick type and the introduction of tri-state functionality. The newly introduced tri-state functionality refers to the on/off control of an individual Brick utilizing a tri-state voltage signal. This signal is so named as it can be set to one of three voltages namely the start, run and disable voltages. These voltages are 15 V, floating and 0 V, respectively.

The Phase-II upgrade Brick, of which there will be 2048 installed within TileCal, provides a nominal output current of 2.3 A at 10 V DC. At the centre of its design is the LT1681 controller chip as seen in Figure 2. It is a pulse width modulator that operates at a fundamental frequency of 300 kHz. The pulse width is controlled via two inputs, the first of which is a slow feedback path that monitors the feedback voltage with a bandwidth of approximately 1 kHz. The second input is a fast feedback path that monitors the current through the low-side transistor on the primary side. The LT1681 provides an output clock to the Field Effect Transformer (FET) driver, which perform the switching on the primary side. The design utilizes synchronous switching, that is, both the high-side and low-side transistors turn on and conduct for the duration that the output clock is in the high state, and both are off when the clock is in the low state. When the FETs conduct, current flows through the primary windings of the transformer, which then transfers energy to the secondary windings. A buck converter is implemented on the secondary side of the transformer. The output side also contains an additional inductor-capacitor stage for the filtering of noise. Voltage feedback for controlling the output voltage is provided. The V8.4.2 Brick utilizes the same protection circuitry implemented on previous iterations of the Brick. The purpose of this circuitry is to initiate a trip of the Brick if operating parameters exceed a specified range from nominal. The design utilizes three types of inbuilt protection circuitry, Over-Voltage Protection, Over-Current Protection (OCP), and Over-Temperature Protection (OTP). These circuits, if activated, initiated an immediate shutdown of the Brick. Their activation depends on the thresholds provided in Table 1.

3. Burn-in Procedure as part of Quality Assurance Testing

The reliability of a manufactured electronic device, such as a Brick, can differ from its predicted design reliability, at both the component and system levels, due to latent and patent defects. To address this phenomenon quality assurance testing is to be undertaken on all LVPS Bricks post-manufacturing [7]. The purpose of which being to increase the reliability of the surviving population by screening out the 'weak' sub-population of Bricks. The finalized sequential quality assurance procedure is partitioned into five distinct tests, namely an automated visual inspection, x-ray scan, initial testing, burn-in and final testing . Each test plays a specific role in ensuring the high reliability of the Brick population once installed on-detector. Initial and Final testing utilize the same test apparatus and procedure. They are so named due to their occurrence pre or post burn-in, respectively [8]. Both tests evaluate various Brick performance metrics and serve to ensure that the Brick under test is operating within its design specifications.

Table 1. Preliminary Phase-II upgrade Brick burn-in parameters, nominal Brick operating parameters and relevant protection circuitry trip points.

Parameter	Burn-in	Nominal	V8.5.0 Protection circuitry trip points
Operating temperature	60° C	35° C	70° C
Load	5 A	2.3 A	6.9 A
Run-time	8 hours	-	-

System level burn-in of the entire manufactured Brick population is to be undertaken. This as some patent and/or latent defects may not have been detected up to this point. Burn-in is primarily focused on detecting patent defects which appear during the early life of the Bricks but it should be noted that latent defects, that usually appear during normal operation, can be converted into patent defects via external overstress. Burn-in testing involves subjecting the Bricks to a burn-in procedure in which they are exposed to sub-optimal operating conditions, such as increased operating temperature and applied load, which function to stimulate failure mechanisms within the 'weak' Brick population. This Brick population is so named due to their propensity to exhibit failures or performance degradation. These Bricks need not experience a catastrophic failure during burn-in but should be easily identifiable during final testing. It is worth emphasizing that burn-in does not improve the reliability of an individual Brick but rather the reliability of the surviving brick population as any identifiable 'weak' bricks are removed from the population. If their weakness can be identified they will be repaired and subjected to the quality assurance procedure again. This process will repeat until the brick passes the entire quality assurance procedure or is deemed irreparable. A custom burn-in apparatus is required to facilitate the burn-in procedure. The development of this apparatus is considered below.

4. Burn-in Test Station

The burn-in station is of an iterative design similarly to that of the Bricks it is tasked with applying a burn-in cycle to. The key design requirement for the latest burn-in station is that it is able to consistently apply the burn-in procedure. This requirement is coupled with the necessity that its operation is simple and that it is safe for non-experts to operate.

The burn-in station can be decomposed into four distinct elements, namely the test-bed, the temperature control system, hardware and software. The test-bed primarily functions to contain the majority of the burn-in station hardware and the Bricks undergoing the burn-in procedure. The test-bed is fully enclosed reducing the impact of the outside environment on the operating temperature of the Bricks and makes use of thermal/electrical insulation to prevent internal water condensation as well as potential electrical shorts while also being physically grounded.

A temperature control system is implemented to control the operating temperature of the Bricks, a key burn-in parameter, during burn-in as well as cool the Dummy-loads to which they provide power. The cooling system utilizes a commercial external water chiller that maintains the Bricks at the desired temperature set point. This temperature can be increased or decreased allowing for the Brick burn-in operating temperature to be set. The burn-in station hardware and software is discussed in sections 4.1 and 4.2, respectively.

4.1. Hardware

As depicted in Figure 4, the burn-in station hardware is composed of a Personal Computer (PC), a 200 V DC power supply, various custom Printed Circuit Boards (PCBs), electronic components, connectors, wiring, cooling plates and a mechanical chassis presented as the test-bed. The PCBs are subdivided into four types, the Main Board (MB), the Brick Interface Board (BIB), the Load Interface Board (LIB) and the Dummy Load Board (DLB). These PCBs receive 220 V AC mains power which is then rectified using DC-DC

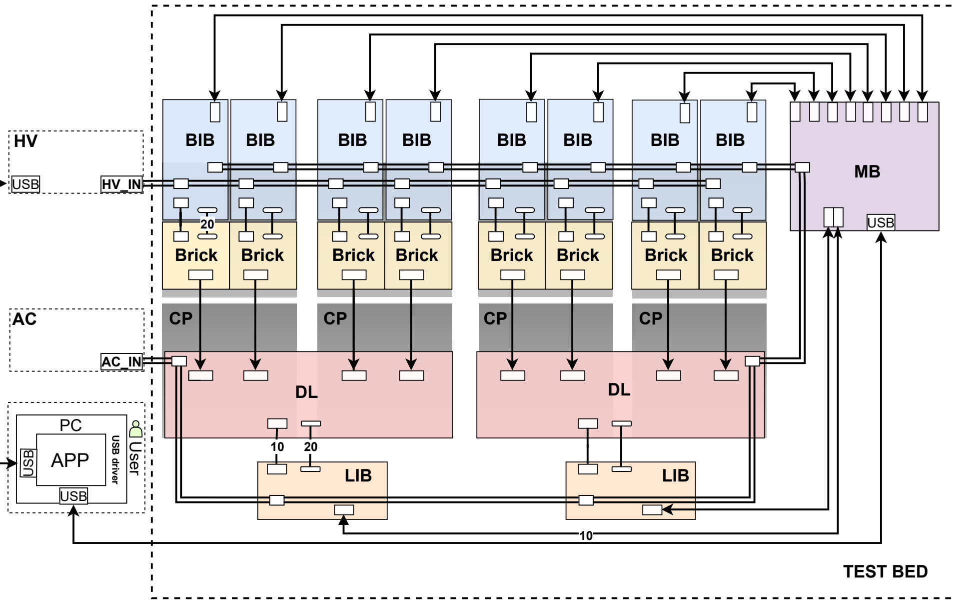

Figure 3: Functional block diagram illustrating the burn-in station hardware.

converters to supply power to the active components mounted on the PCBs. There is one MB per burn-in station responsible for addressing and demultiplexing of the interface boards. This allows a Burn-in LabVIEW Application (BLA) running on a PC to communicate via Universal Serial Bus (USB) to a Universal Asynchronous Receiver-Transmitter (UART) interface from the Programmable Interface Controller (PIC) of the MB to each PIC of the interface boards. A program on the PIC of the MB sequentially polls each of the interface boards to perform a particular task. There are eight BIBs per Burn-in station with one associated with each of the 8 Bricks undergoing the burn-in procedure. These BIBs provide control and monitoring of their respective Bricks while the LIB provide control and monitoring of a dummy load connected to the respective Brick. A single Brick is connected to a BIB for readout of measurements where the Brick output voltage is connected to a DLB that incorporates closed-loop Voltage Controlled Current Sink (VCCS) circuitry. The Dummy Load Boards (DLB), Make use of 4 VCCS that use high precision op-amps and N-channel MOSFETs that are affixed to the Cooling Plates (CP) to dissipate the heat generated.

4.2. Software

The Burn-in LabVIEW Application (BLA) and PIC firmware were originally developed by Argonne National Laboratory in 2006 for the version 7 Bricks. During testing and development of the burn-in station, the BLA has undergone major revisions in terms of improving code readability while only minor changes were made to the High Voltage (HV) power supply instrumentation drivers and the ADC channel configurations of the Interface Boards (IBs). The software required for the operation of a Burn-in station can be divided into three categories namely the BLA, the PIC firmware and the PVS60085MR HV power supply instrumentation drivers.

5. Preliminary Burn-in Procedure

The Burn-in procedure subjects the Bricks to sub-optimal operating conditions that function to stimulate failure mechanisms within the Bricks and is the subject of ongoing research. These conditions need to fall within the extrema allowed for by the Brick design and operation. There are two reasons for this. Firstly, the failure mechanisms stimulated must be of the kind that can be experienced during operation within TileCal such as an increased operating temperature is related to allow for effective Burn-in. The second reason

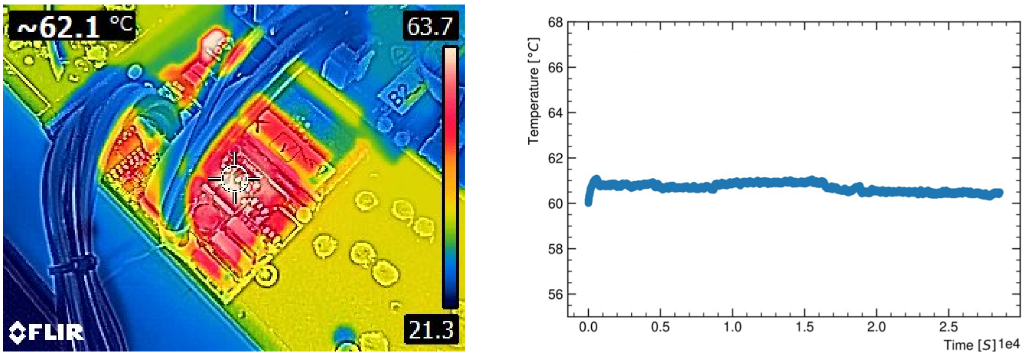

Figure 4. Thermal image of a Burn-in station undertaking burn-in of a Brick (Left). A temperature stability plot of a Phase-II Upgrade LVPS Brick undergoing burn-in testing (Right).

for limiting the Burn-in parameters provided in Table 1 to within the Bricks final operating extrema is due to the Bricks inbuilt protection circuitry. A Brick will initiate a trip if the OCP or OTP trip parameters are met during burn-in. The run-time of the burn-in procedure is an equally important parameter. One needs to maximize the efficacy of the burn-in process while maintaining a practical time frame for the burn-in of the entire Brick population. The above points combined with previous experience obtained through the burn-in of the V7.5.0 Bricks were considered resulting in the burn-in parameters provided in Table 1 being selected.

6. Preliminary Burn-in Results

The Brick undergoing burn-in can be observed in Figure 4 (Left). The burn-in temperature parameter is being met with the observed hot spot resulting from the primary-side switching MOSFETs due to switching losses as expected. The thermistor utilized for the on-Brick measurements is located adjacent to these MOSFETS and is utilized in the Bricks OTP circuitry. The temperature monitored during the Burn-in procedure is illustrated in Figure 4 (Right). The Burn-in temperature is stable with a mean value of 60.7 °C and a standard deviation of $\sigma = 0.2$ °C.

7. Discussion

The ATLAS Phase-II Tile-calorimeter low-voltage power supply transformer-coupled buck converters burn-in station is in a mature stage of development with preliminary hardware and software testing having taken place. Favorable results have been obtained with regards to the burn-in stations temperature stability with ongoing research into the applied load stability. The finalization of the burn-in procedure will take place after the application of the preliminary burn-in procedure to the pre-production batch of 104 Bricks which is expected to take place by the end of 2023.

Funding: This research was funded in part by the National Research Foundation of South Africa, grant number 123017.

Data Availability Statement: Not applicable

Conflicts of Interest: The author declares no conflicts of interest.

References

1. The ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *Journal of Instrumentation* **2008**, *3*, S08003–S08003.
2. CERN Document Server. Available online: https://cds.cern.ch/record/1095927 (accessed on 25 July 2022).
3. CERN. High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report. *CERN Yellow Reports* **2015**.
4. CERN Document Server. Available online: https://cds.cern.ch/record/2285583 (accessed on 25 July 2022).

5. Mckenzie, R. on behalf of the ATLAS Tile Calorimeter System. The ATLAS Tile Calorimeter performance and its upgrade towards the High Luminosity Large Hadron Collider. In Proceedings of the 28th in the series of annual workshops on Deep-Inelastic Scattering (DIS2021) and Related Subjects., Stony Brook University, United States of America, (12 April 2021), (171).
6. Mckenzie, R. on behalf of the ATLAS Tile Calorimeter System. TUpgrade of ATLAS Hadronic Tile Calorimeter for the High Luminosity LHC. In Proceedings of The Ninth Annual Conference on Large Hadron Collider Physics (LHCP2021), online, (7 June 2021),.
7. Mckenzie, R. Quality assurance testing of the ATLAS Tile-Calorimeter Phase-II upgrade low-voltage power supplies. In The Proceedings of SAIP2019, the 65th Annual Conference of the South African Institute of Physics, edited by Prof. Aletta Prinsloo, (UJ), Online, South Africa, (23 July 2021); (138).
8. Nkadimeng, E.; Mckenzie, R.; Moeyedi, S.; Nemecek, S.; Hadavand, H.; Mellado, B.; Van Rensburg, R. A monitoring and control test bench for assessing the upgraded low voltage power supplies for the ATLAS Tile Calorimeter Phase-II Upgrade front-end electronics. *Arxiv* **2022**.