PROCEEDINGS OF SCIENCE

Development of the BCM prime system and readout for ATLAS

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The High Luminosity upgrade of the Large Hadron Collider will increase the LHC luminosity and with it the density of particles on the detector by an order of magnitude. For protecting the inner silicon detectors of the ATLAS experiment and for monitoring the delivered luminosity, a radiation hard beam monitor has been developed. A set of detectors has been developed based on polycrystalline Chemical Vapor Deposition diamonds and a new dedicated radiation-hard front-end ASIC. To satisfy the requirements imposed by the HL-LHC, our solution is based on segmenting diamond sensors into devices of varying size and reading them out with new multichannel readout ASICs divided into two independent parts, each of them serving one of the tasks of the system.

This document describes the system design including detectors, electronics and the ATLAS FPGA FELIX based readout. Additionally, it presents preliminary results of the readout with data from beam tests from 2023 at the SPS beam line at CERN.

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1. Introduction and BCM concept

The CERN Large Hadron Collider, located in Geneva, will be upgraded to the High-Luminosity LHC in the coming years. The collision rate will increase up to 200 inelastic p-p collisions per bunch crossing. The ATLAS detector will also be upgraded including the installation of a new all-silicon Inner Tracker (ITk) [1] detector. The HL-LHC radiation conditions will require a reliable Beam Conditions Monitoring (BCM) system.

Within the new ITk, the upgrade of the BCM system (BCM') will monitor background activity to safeguard the ITk. The system is designed to trigger the abort of the LHC beam under dangerous particle showers, ensuring compliance with the harder radiation specifications of the HL-LHC. The BCM' will also function as a luminometer for ATLAS.

The BCM' system will utilize polycrystalline Chemical Vapor Deposition (pCVD) diamond sensors embedded in modules equipped with the Calypso Front-End (FE) ASIC. Its readout architecture will be based on the ATLAS Front-End Link eXchange, FELIX [2] system. The new FPGA based system is set to replace the legacy ROD and ROS architecture.

The BCM' will be installed inside the ITk on two dedicated BCM' rings at $z = \pm 1.875$ m (6.25 ns) on either side of the interaction point, as depicted in Fig. 1. The z position remains the same as that of the previous BCM. Background events are identified based on Time-of-Flight measurement; and out-of-time events indicate possible beam instabilities. Background particle showers generated upstream of the experiment generate early signals in the upstream ring at $t \approx -2z/c \approx 12.5$ ns (equivalent to half an LHC clock cycle); these are followed by the collision and downstream background signals at the nominal $t = 0$. An excessive abundance of signals that are out-of-time indicates unusual beam conditions, necessitating a beam abort.

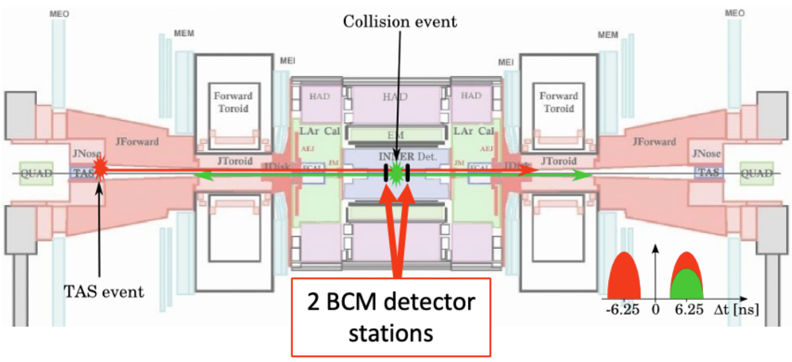

Figure 1: The time-of-flight concept for the discrimination between collision (represented in green) and background signals (represented in red) in the BCM'.

2. Front-end electronics and sensors

The FE Calypso ASIC, and its latest version Calypso_D, is engineered using the TSMC 65 nm process technology with a minimal die size of 2×2 mm^2 [3]. It's suitable for environments enduring a total ionizing dose up to 3 MGy. It has two output channels, one for luminosity and one for abort. Each channel with gain and constant fraction discriminator (CFD) settings features a 1 ns rise time, 200 ps jitter, 200 e^- noise and 2 pF detector capacitance. LVDS output signals are sampled to measure time over threshold (ToT) and time of arrival (ToA) information based on high and low states. The configuration of Calypso is accomplished through the I^2C protocol.

The BCM' sensor array comprises pCVD diamonds from US vendor II-VI [4]. This set includes a 3D pCVD diamond, two planar 10 × 10 mm^2 pCVD diamond detectors for luminosity measurements, and a planar 5 × 5 mm^2 pCVD diamond dedicated to beam abort functionality. All pCVD diamond detectors will be 500 μm thick. They were tested at 2022 and 2023 test beam campaigns [5]. The latest results [6] demonstrated an analog signal-to-noise ratio of 25 at ±1000 V. Additionally, threshold measurements with 128 CFD ~100 e^- steps show low noise occupancy across all the tested channels and a high efficiency > 99% for multi-minimum ionizing particles (MIPs) at the 5σ threshold.

The pCVD diamond and Calypso_D were tested at the H6 beam line of the SPS at CERN, with a 120 GeV pion beam using a MALTA planes-based telescope [7]. MALTA, a monolithic pixel detector [8], based on TowerJazz 180 nm CMOS technology developed at CERN, features a 2×2 cm^2 active area with a 512×512 pixel matrix, each positioned at 36.4 μm pitch. The telescope uses 6 tracking planes plus a scintillator performing a reconstructed track spatial resolution of 4.1 μm and reconstructed track timing resolution of 2.1 ns.

3. BCM' readout

Figure 2 illustrates a BCM' ring model. Each carbon fiber-cooled ring structure will house 4 modules each capable of detecting multi-MIP signals for abort functions and single-MIP signals for luminosity measurement and background monitoring. The modules also include the slower, backup Beam Loss Monitoring (BLM) protection system.

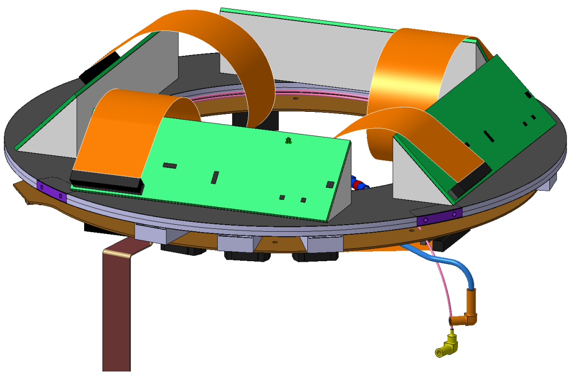

Figure 2: Prototype model of the BCM' ring. The sensors housing PCBs are tilted 45° to improve particle detection.

Figure 3 outlines the BCM' system's main components. Within each module, the Calypso FE processes sensor signals, providing a LVDS output in semi-digital format for each sensor. The signal remains high when the charge exceeds the programmable threshold and low otherwise. The duration of these high and low states allows the extraction of the ToT and ToA data at the readout. Each module includes two radiation-hard LAPA drivers to amplify signals transmitted over 5 m of twisted pair (Twinax) cable to the next readout component. The modules are mounted on the BCM ring and connected via flex cables to an auxiliary PCB (aPCB) with PP0 services and the Opto Panel, following a design akin to the Pixel Inner System.

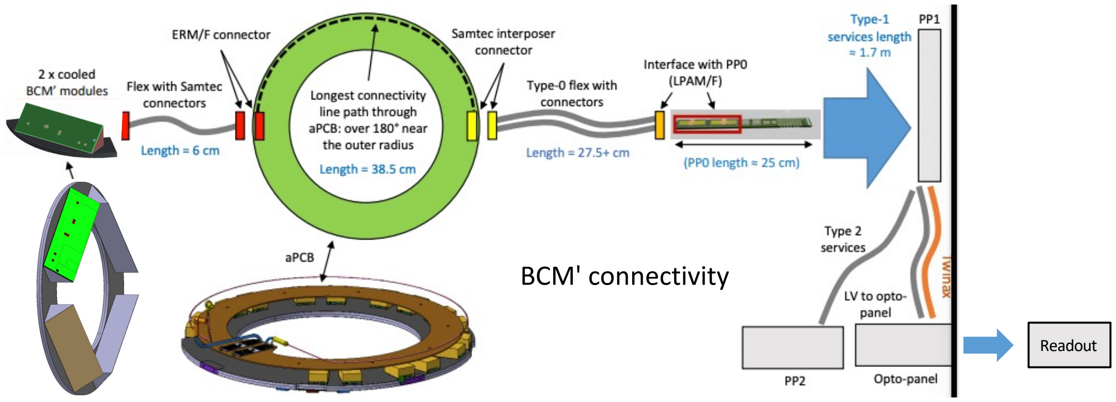

Figure 3: Diagram of the main components of the BCM' readout chain.

Eight optical transceiver boards (Opto Boards) [9] designated for the BCM' convert electrical signals from LAPA to optical signals at a rate of 1.28 Gbps. The optical fibers running between the detector and services caverns transmit 96 e-links, encapsulating semi-digital data in LPGBT frames [10]. Fig. 4 depicts the simplified data path from FE to FELIX and the command data from FELIX to FE.

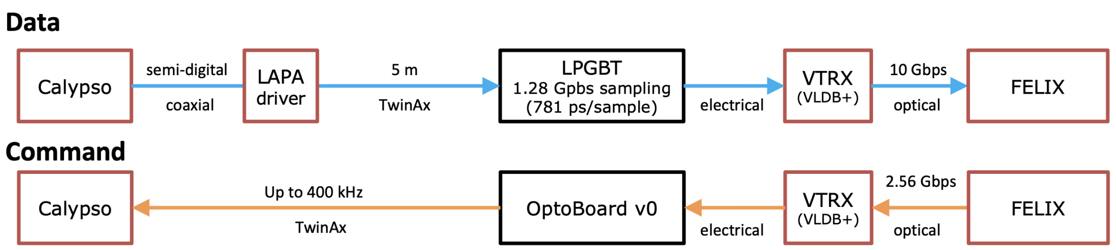

Figure 4: Flow diagram of the BCM' readout data and command basic path.

The FPGA-based FELIX readout system, located in the services cavern, continuously processes data. It will convert incoming optical signals from the Opto Boards, package the data into data-packets containing ToT and ToA measurements, and send an analog beam abort signal when necessary. It will also transmit data commands to configure all FEs using I^2C.

A prototype of the BCM' specific decoding block for the FELIX firmware has been developed leveraging the ITk Phase-II Pixel firmware architecture. This block calculates the ToT of a signal from the semi-digital data and measures its ToA with respect to a 40 MHz clock. This allows the detector to provide proper BCID tagging and L1A information for each signal received. This process is executed in parallel for all the e-links. The output of the decoding block is a fragment of variable size for each e-link made out of 32-bit chunks. The first chunk contains the full extended L1ID. The following chunks contain a 6-bit ToA, a 6-bit ToT, a 12-bit BCID, and a 6-bit L1 delay counter, and 2 reserved bits forced always to high, as shown in Table 1. Up to 5 chunks are allowed per L1ID. The data transmission from FELIX to the next element in the read-out chain is done by one fragment at a time, to ensure its proper decoding. Additionally, a zero-suppression flag is available in the firmware, that allows suppression of the fragment for a given L1ID if no signals have been recorded for it.

Position	31:30	29:24	23:12	11:6	5:0
1	Extended L1ID				
2	11(reserved)	L1 Delay Counter	BCID	ToT	ToA
3	11(reserved)	L1 Delay Counter	BCID	ToT	ToA
4	11(reserved)	L1 Delay Counter	BCID	ToT	ToA
5	11(reserved)	L1 Delay Counter	BCID	ToT	ToA
6	11(reserved)	L1 Delay Counter	BCID	ToT	ToA

Table 1: BCM' raw data fragment. Positions 1 and 2 are required, 3 to 6 are only generated if necessary.

4. Tests results

In 2023, a basic setup of the FELIX BCM' readout chain was tested at the H6 SPS beam line at CERN. This setup comprised four channels of a Calypso C, connected to a LAPA driver, which in turn was linked to a VLDB+. The VLDB+ was optically connected to FELIX.

Figure 5 presents preliminary data from these tests. On the left, we observe a consistent distribution of ToT hits in ns at the 60 CFD threshold ~100 e^- steps. The ToT, which is determined by the energy deposition, is influenced by the threshold parameter. The plot on the right illustrates the time measurement distribution between the delayed signal, held in a FIFO buffer, and the arrival of the L1A signal from the telescope's trigger logic unit (TLU). The duration of the delay can be configured. Figure 6 shows the time line of key events in the firmware, arrival of the signal from Calypso, arrival of the signal from the TLU and the delayed signal.

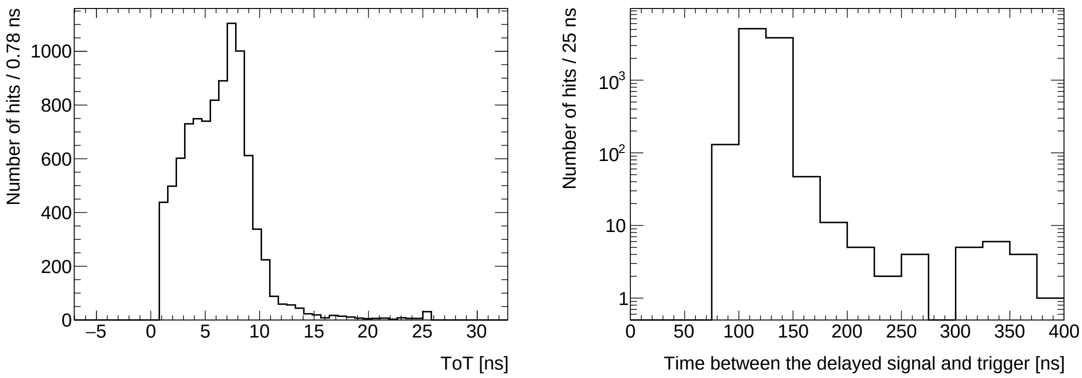

Figure 5: FELIX firmware readout of Calypso C module measurements at the SPS. On the left: Number of hits as a function of ToT in ns. On the right: Number of hits as a function of the measured time in ns between the stored signal and L1A.

5. Conclusions

The BCM' detector is currently in development for the upcoming ATLAS High-Luminosity upgrade. It will measure luminosity and protect the inner components of the experiment. The

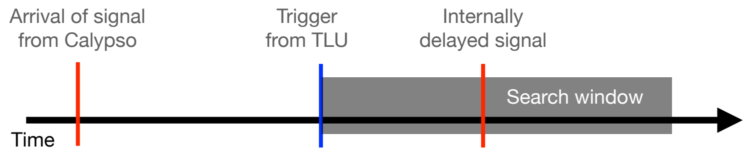

Figure 6: Time line of events in the firmware.

latest versions of the Calypso FE have yielded satisfactory results, aligning well with the specified requirements. Additionally, a preliminary setup of the FELIX readout chain has been successfully demonstrated and tested under realistic conditions in a beam line for the first time. These initial tests indicate that the readout system is capable of accurately measuring ToT and ToA, as well as transmitting online data effectively without data loss. Certain firmware functionalities, such as the abort signal, are pending implementation and will be addressed shortly. Comprehensive testing of the final modules, along with the full suite of services, is scheduled to commence in 2024.

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