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SciFi Front-End Electronics: calibration and results on detector performance

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Abstract: The LHCb Experiment is commissioning its first upgrade to cope with increased luminosity of LHC Run3, being able to improve on many world-best physics measurements. A new scintillating fiber-based tracker (SciFi) replaced the outer and inner trackers, providing improved spatial resolution and granularity for the new LHCb trigger-less era, with a readout capable of reading zero suppressed data from ~524k channels at 40 MHz. The fully automated calibration of SciFi Front-End Electronics is based on dedicated software tools and operational procedures, validated during SciFi commissioning. This paper describes the design, implementation, and calibration of SciFi electronics and presents results showing the detector performance after commissioning.

Keywords: Detector alignment and calibration methods (lasers, sources, particle-beams); Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Front-end electronics for detector readout; Particle tracking detectors

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Contents

1 Introduction

The LHCb experiment was designed to investigate CP violation and look for indications of physics beyond the Standard Model in the mixing and decays of particles that contain beauty (b) or charm (c) quarks. Given the topology of these events, outstanding vertex and tracking systems are essential.

In Runs I and II, LHCb collected a total integrated luminosity of almost $10\,\mathrm{fb}^{-1}$ at a leveled instantaneous luminosity of $4 \times 10^{-32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. During LHC Long Shutdown 2 (LS2), between 2018 and 2022, LHCb received its first upgrade [1] to run at five times the luminosity, significantly expanding the physics reach of the experiment. Thus, the accumulation of ~$50\,\mathrm{fb}^{-1}$ of integrated luminosity is expected until 2030, when the next major upgrade campaign is expected [2].

The Scintillating Fiber Tracker (SciFi) is a new LHCb tracker for LHC Run 3 and 4, replacing Inner and Outer Trackers [3, section 5]. Covering an area of $340\,\mathrm{m}^2$, the detector uses a novel technology with more than 10′000 km of a 250 µm diameter blue-emitting scintillating fiber and has been designed to achieve a spatial resolution better than 80 µm, hit efficiency better than 99%, and the ability to handle higher luminosities due to its higher granularity and a triggerless 40 MHz read-out. The data delivered by SciFi feeds the new tracking-based online event filter, allowing an increase in the selection efficiency for numerous physics event types, as compared to the previous hardware trigger.

These substantial improvements posed new challenges to on-detector electronics, which has to process signals from 4096 linear arrays of 128-channel Silicon Photomultipliers (SiPM) each, placed at the fiber ends, and cooled to −40 °C. The low photo-electron statistics require a very sensitive digitizer, the high channel density (4 channels per mm) demands careful PCB design, and possibly most challenging, the sheer data volume requires high-speed data transmission and ultimately needs to implement advanced zero-suppression clustering in the Front-End Electronics.

2 SciFi Front-End Electronics overview

SciFi Front-End Electronics (FEE) devices are assembled in Front-End Boxes. Each box consists of two HalfROBs, identical sets of interconnected electronic modules that are, from the control's point of view, an FEE Device Unit. A HalfROB is made up of 1 Master Board, 4 Cluster Boards, 4 Pacific Boards, and 1 Light Injection System (LIS) device, as illustrated in figure 1.

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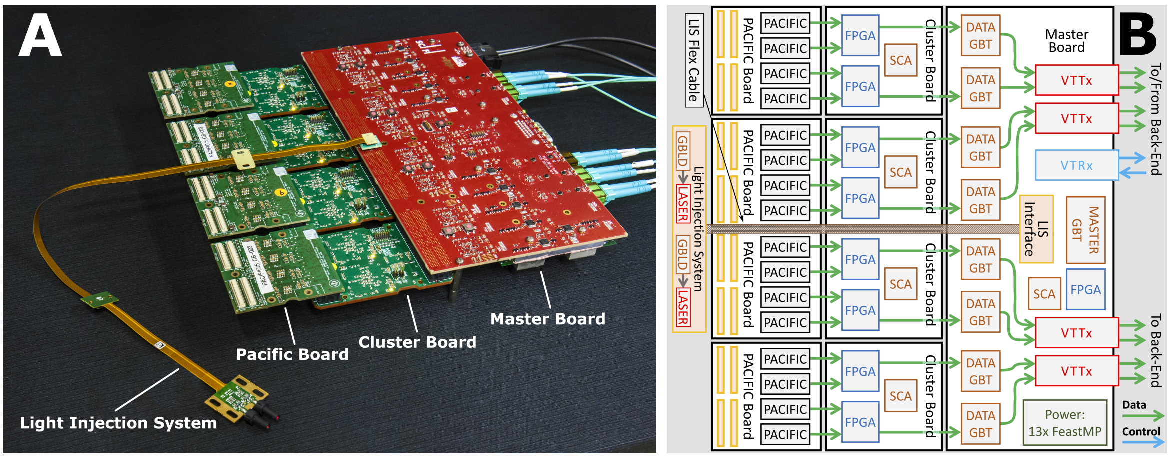

Figure 1. Elements of a SciFi FEE Device Unit assembled outside the Front-End Box casing (A) and the corresponding block diagram with the data paths indicated (B).

Each Pacific Board hosts four custom-made PACIFIC [4] ASICs, which receives SiPM analog signals and provide shaping, charge integration over time, and discrimination. This module also hosts the infrastructure for SiPM biasing and monitoring (voltage and temperature). The need to reduce the data volume shapes the FEE design and restricts the digitized output of each 250 µm SiPM channel to 2 bits, encoding signal discrimination over three programmable thresholds.

The Cluster Board hosts two flash-based radiation-tolerant MicroSemi Igloo2 [5] M2GL090T FPGAs for clustering, data encoding, and Timing and Fast Control (TFC) handling. Each Cluster Board receives 20.48 Gbps of raw data from four PACIFIC ASICs, 5.12 Gbps each, and delivers 8,96 Gbps of encoded data for two 4.48 Gbps Data Links (one per FPGA) providing the data reduction needed. The choice to use an FPGA is supported by the complexity of the task combined with the relatively low radiation doses ($\leq 80\,\mathrm{Gy}$) expected [6] in this region, and its usage in this environment has been validated by a research program. Each Cluster Board also hosts one GBT-SCA [10] device to provide a bridge for slow control signals from devices on the Cluster and Pacific Boards.

The Master Board is the interface between four Cluster Boards, the LIS, the LV/HV distribution, and the Back-End. This module provides data serialization and FEE management. Some devices developed by CERN are widely used: 9x GBTx [7] ASICs, 4x VTTx, 1x VTRx [9], 1x GBT-SCA, and 13x FeastMP [11] DC-DC converters. A GBTx is operated as a bidirectional transceiver and identified as MasterGBT, responsible for the slow and fast control interfaces and the first level of time distribution. Eight GBTx identified as DataGBTs are set up as simplex transmitters, sending data from the FPGAs to the Back-End. The PLL/DLL resources of these devices also play a role in the timing distribution, providing multiple derived clocks to the readout. Furthermore, a GBT-SCA provides a bridge for onboard slow control signals and analog readings, and a MicroSemi Igloo2 M2GL005 FPGA is used for FEE management, some of the TFC handling, and to control the LIS.

The LIS consists of the flex cable and a small board with two GigaBit Laser Driver (GBLD) [8] ASICs and two lasers, providing a controlled light source for detector testing and calibration.

The SciFi detector is made up of 256 front-end boxes, covering 524′288 SiPM channels grouped onto 4′096 Data Links, at 4.8 Gbps each, resulting in a combined data throughput of 19.7 Tbps. 512 bidirectional links are used for detector control and time distribution, at 2×4.8 Gbps each.

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A dedicated FEE tester [12] has been developed and is used for the quality assurance of the Front-End Boxes. This test system was extensively used for detector assembly and is expected to remain operational during the lifetime of the detector for its maintenance.

3 Front-end electronics calibration procedures

The complex design of SciFi detector requires several reprogrammable parameters to accommodate changes in operational conditions, like fiber signal deterioration and increased SiPM noise due to radiation damage, making continuous recalibration crucial to retain the detector's best performance during its lifetime. Databases and software tools were developed to fully automate the process of taking data, analyzing them to determine the best operational settings, and transferring them to the detector electronics configuration. A description of the database environment is provided by [13].

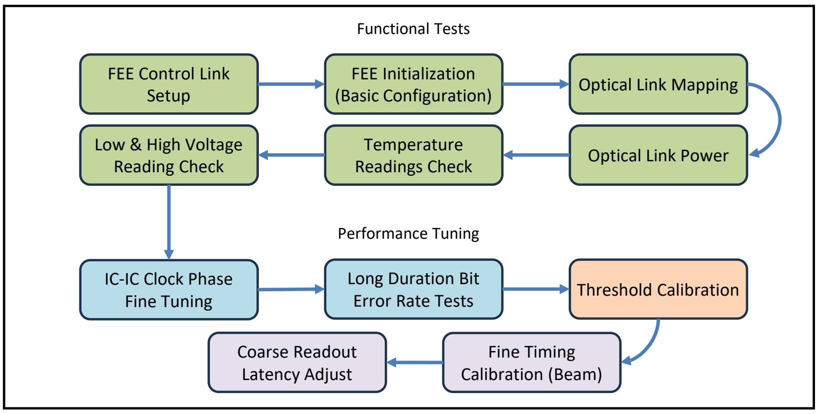

Figure 2. Flow Diagram of steps during FEE Commissioning.

The FEE commissioning procedure consists of a sequence of checks and calibration procedures to integrate an FEE device into the system, with the aim of ensuring the quality of crucial optical links, SiPM connection, and geographical mapping, among other checks, and to calibrate for compensation of parameters such as manufacturing tolerances, cabling, and SiPM characteristics. This procedure is illustrated in figure 2 and is expected to be executed during detector assembly and later, every time a FEE Device Unit has to be replaced at the SciFi detector. Additionally, performance-tuning operations should be performed during detector lifetime to compensate for component aging or changes in environmental conditions.

Calibration procedures are mainly based on the LHCb standard step-scan mechanism (configured with the help of the Scan Creator and Recipe Creator software), data processing based on custom-made analysis software, and the creation of a calibrated recipe with the help of the Recipe Creator software. The workflow for a Threshold Scan with Light Injection procedure was taken as an example of this methodology and is illustrated in figure 3.

With 58 adjustable-phase interdependent clock paths per FEE device unit (total of 29k7 in SciFi), timing alignment poses a great challenge. Figure 4 displays the clock paths in a FEE Device Unit and indicates the multiple test pattern sources placed among the system with green and yellow arrows, depending on the pattern type. This infrastructure is intended to be used associated with Bit Error Rate checkers on the Back-End to evaluate data integrity as the clock phases are adjusted.

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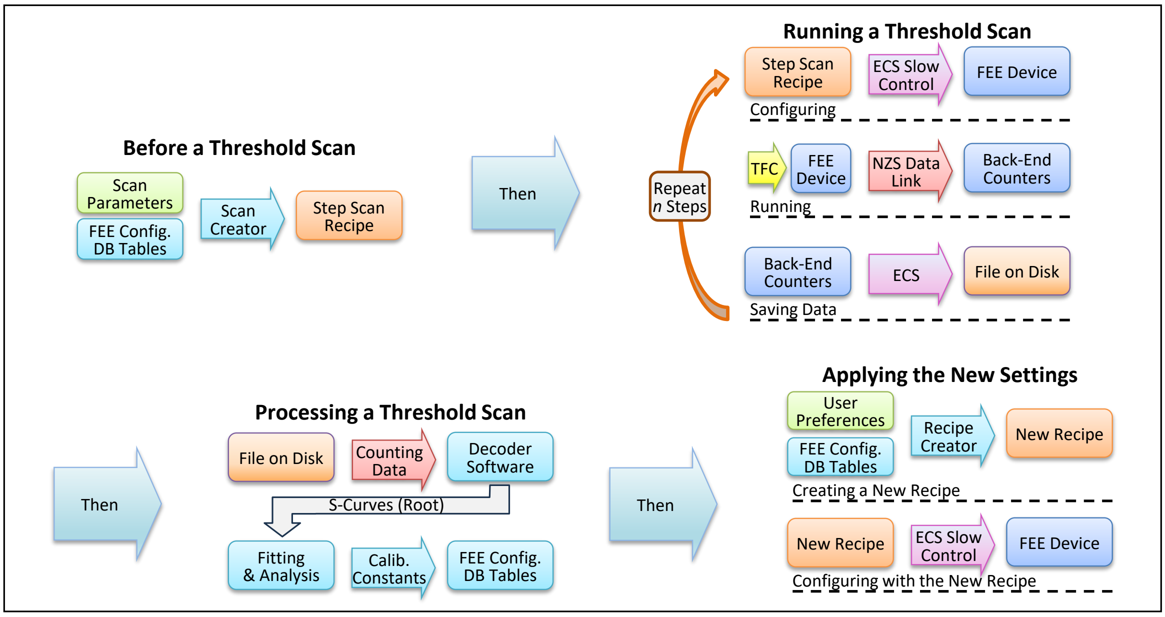

Figure 3. Flow Diagram of steps during FEE Commissioning.

The scheme above is to adjust the intra-FEE clock phases to meet Setup/Hold time requirements and ensure reliable digital data transmission, a timing calibration that should not be confused with the time alignment with respect to hits from the LHC collisions. This follows a similar workflow as for the already presented Threshold Scan, stepping the phase of clock lanes from Master to Data GBTs, adjusting the clock domain crossing accordingly, and searching for the best hit efficiency.

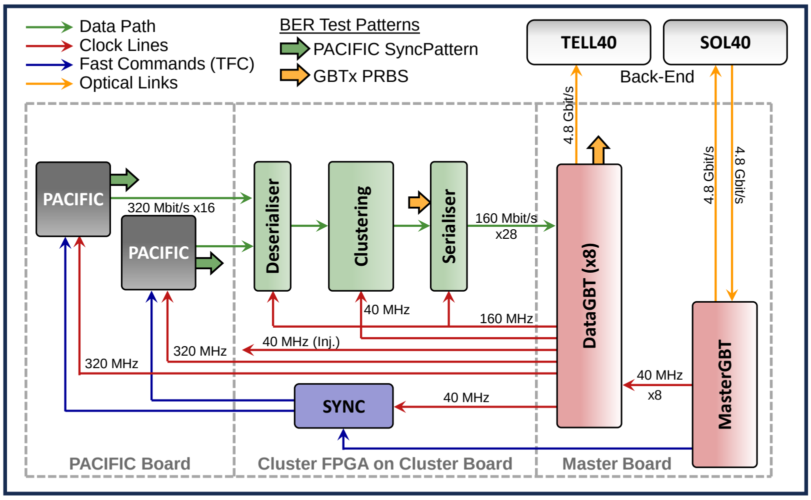

Figure 4. Diagram of Clock and Signal paths related with Time Alignment in a SciFi FEE Device Unit.

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4 Results on detector performance

The installation of the SciFi detector in the experimental area was completed in April 2022, and the calibration procedures presented in section 3 are being used extensively. Although the commissioning activities are still underway, it is already possible to extract some preliminary qualitative information about the detector performance.

In figure 5, two plots were chosen for this purpose. The first (A) came from data taken on the last day with the LHC beam in 2022, and is a good indicator of the detector response to collision events. In this graph, the number of clusters delivered by the clustering algorithm (and after software decoding) is plotted as a function of the channel number for a selected detector layer. The observed distribution is consistent with the theoretical expectation and with previously simulated events.

The second plot (B) presents a preliminary measurement of the unbiased SciFi hit detection efficiency with LHCb Run 3 data. To determine the hit detection efficiency, the layer being studied was excluded from the track reconstruction, and the tracks were matched to SciFi hits with the closest approach between the track and the hit being no more than 1.0 mm. A more comprehensive description of this methodology can be found in ref. [15]. The observed drop at the edges is due to the gaps between detector elements (Fiber Mats), and the drop in the center is due to a small gap between the two SiPM 64-channel dies that are glued together to compose a 128-channel array.

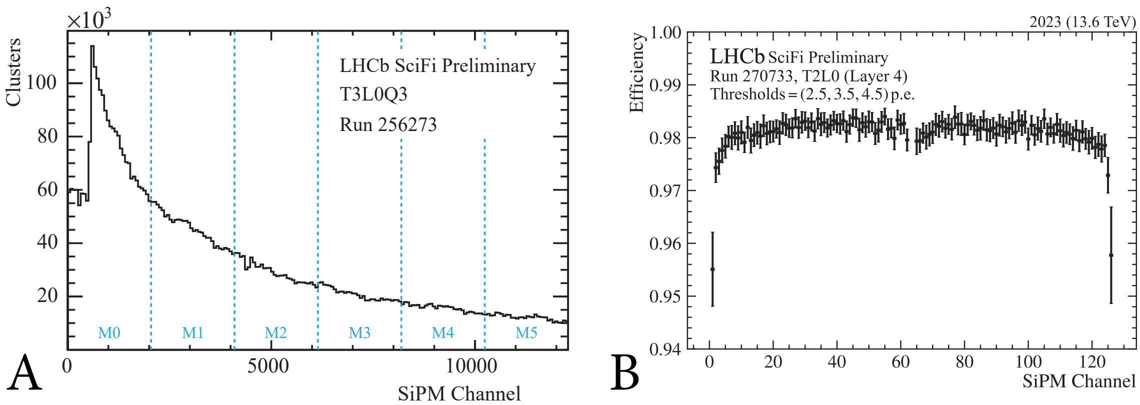

Figure 5. (A) Number of clusters as a function of the SiPM channel position for Run 256273, taken in 28 November 2022. Reproduced from [14]. CC BY 4.0. (B) Average hit detection efficiency of all SiPMs in the layer under study per channel, zoomed in y-axis range, for Run 270733, taken in 16 July 2023. Reproduced from [15]. CC BY 4.0.

5 Conclusions

After a long road of R&D, manufacturing, assembly, and installation, SciFi Tracker is now completely integrated into LHCb systems and continuously operates to deliver data for the experiment. All FEE devices were assembled, tested, installed, and proven to be functional for operation. A stable and tested firmware release is programmed on FEE FPGA devices which are working without problems. The calibration methodology described in this paper is implemented, and the detector is operating well within the performance required for the present stage. Some additional improvement is expected as the final commissioning activities are well underway.

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