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LHC BLM SYSTEM AUTOMATIONS FOR FAULT DETECTION, DIAGNOSIS, AND ISSUE TRACKING

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Abstract

One of the principal roles of CERN's Beam Loss Monitoring (BLM) system pertains to the protection of the Large Hadron Collider's (LHC) superconducting magnets against beam-induced quenches. Thus, continuous monitoring of the performance of the BLM system is essential to ensure the high reliability and availability of the LHC BLM protection system. This paper focuses on the architecture of a novel data pipeline with implementations on monitoring the communication status between the 864 acquisition tunnel modules that digitize the analog beam loss measurements and the 432 processing surface modules that determine and act upon the criticality of the beam losses. The discussed pipeline replaces an older batch Extract-Transform-Load (ETL) process, which published daily BLM status reports, in favor of a streaming ETL process. The new pipeline expands beyond the daily publication of static status reports by exploiting real-time data analysis and processing enabling the live assessment of the system's status via online fault detection, web-based dashboards, and automated Jira issue generation enabling issue tracking. Future development on the implemented pipeline envisions online machine learning features permitting fault prognosis.

INTRODUCTION

The LHC Beam Loss Monitoring (BLM) system plays a pivotal role in guaranteeing the high availability and reliability of the LHC accelerator at CERN from contributing to the optimization of the accelerator to preventing the quenching of superconducting magnets [1]. The BLM system covers, with nearly 4 000 detectors, the 27 km of accelerator elements and comprises thousands of interconnected components ranging from detectors to processing and acquisition electronic units that generate on the order of several Megabytes of data every second. In addition to the system's built-in redundancies and fail-safe design, due to its criticality and large scale, high-level system-wide surveillance is required in order to maintain high dependability. The benefits of such surveillance on the BLM system comprise the anticipation of issues, planning of interventions, and fast fault identification on occasions requiring immediate response.

This paper focuses on a novel high-level surveillance of the BLM system that is accomplished through a streaming Extract-Transform-Load (ETL) pipeline, coined as BL-ARMA an abbreviation for Beam-Loss Analysis, Reporting, and Monitoring Automations. The new data pipeline replaces the original batch ETL design that was limited to providing static insights on the status of the BLM system. BL-ARMA extracts data from various sources, performs streaming transformations, loads the results into databases and, in addition, performs various automations. By harnessing its real-time analytic capabilities, BL-ARMA enhances the surveillance of the BLM system with features including real-time monitoring, daily status reports, automated fault detection and diagnosis, alerts, and issue tracking. The discussed pipeline is part of the Efficient Particle Accelerator project, which aims to incorporate automations, reporting, anomaly detection and real-time analysis on accelerator systems [2].

BL-ARMA ARCHITECTURE

Prior to implementation, special considerations were given to the design choices of the new streaming data pipeline. The architecture of BL-ARMA aims to exploit on-the-fly data processing and a modular design. In order to accommodate such design features, optimized for CERN's infrastructure, the proposed data pipeline was built upon the Unified Controls Acquisition and Processing (UCAP) framework [3]. UCAP enables the development of event-driven streaming data pipelines through instantiating virtual devices with high throughput processing and pub/sub capabilities.

The modular character of BL-ARMA is accomplished by distributing the pipeline's workload among an ensemble of interconnected virtual devices, each maintaining a designated role. Such a configuration evokes fault-tolerant properties and facilitates the expansion of the pipeline by easily incorporating additional devices. The core processing units of BL-ARMA consist of the Batch-Ingestion, Analysis, Diagnostics, and Reporting devices that are arranged according to Fig. 1.

The role of the Batch-Ingestion device is limited to ingesting data from sources that are updated infrequently such as databases that contain BLM system parameters. The device triggers in a diurnal fashion and consolidates data through merging operations. The resulting information is transmitted to the Analysis device and is stored in buffers for further processing. This acts as a loose coupling connection between the Analysis and Batch-Ingestion devices, increasing BL-ARMA's reliability and robustness against faults localized to individual modules.

Apart from data received from the Batch-Ingestion unit, the Analysis device also ingests measurements from the BLM system at a 1 Hz rate. Its main function consists of performing the core analysis on the raw measurement data to render it amenable to subsequent devices. Most data publications are performed in real-time, however, event-driven publications consisting primarily of data aggregations also

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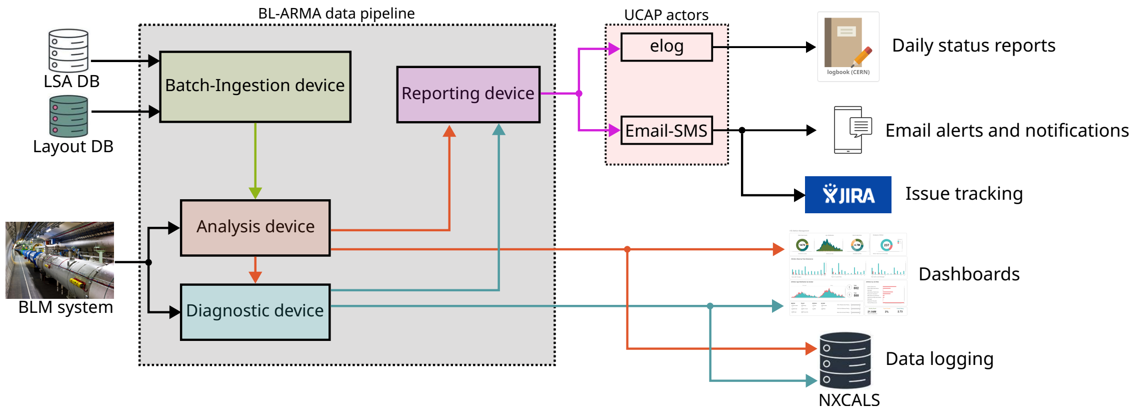

Figure 1: BL-ARMA configuration.

occur. A subset of data produced by the Analysis unit is visualized through dashboards and loaded into the NXCALS database [4], while the rest is transmitted to the Diagnostics and Reporting devices.

The Diagnostics module triggers at a 1 Hz rate, subscribes to the Analysis device and, furthermore, ingests basic diagnostic data from the BLM system. Through this data, the device determines the health status of different areas of the BLM system and ascertains root causes in the case of issues. As part of the fault tolerant character of BL-ARMA, in case of a malfunction of the Analysis device, the Diagnostic device will continue to perform as many diagnostic operations as possible and will acknowledge the missing analysis data. The findings of the Diagnostics device are in part displayed in dashboards, stored in NXCALS, and sent via event-triggered publications to the Reporting device.

The final core device in the BL-ARMA data pipeline consists of the Reporting module, which triggers upon reception of data from the Analysis or the Diagnostics devices. Its primary focus is to present incoming data into a human readable form by creating plots, rendering text, or html tables. The Reporting device communicates its outputs exclusively to UCAP actors that enable actions such as logbook posts or email notifications.

BL-ARMA IMPLEMENTATIONS

The high complexity of the BLM system requires the implementation of separate pipelines to monitor distinct areas of its scope. A principal example of such an implementation consists of the surveillance on the communication status between the BLM system's acquisition and processing electronics. These perform, respectively, the digitization of the analog losses and determine their criticality by comparing them to the BLM threshold settings [5]. The acquisition module, otherwise referred to as Current-to-Frequency Converter (CFC) cards, are installed in the LHC tunnel area and are connected through optical fibers to the processing modules, called Threshold Comparator (TC) cards, which are accommodated in crates located in surface buildings. The harsh environmental conditions paired with the high throughput occasionally result in communication errors. Those are usually mitigated by incorporating redundancies in the system. However, in certain cases, such errors can cause the request of beam extraction by the BLM system. A BL-ARMA pipeline surveils the communication status between the TC and CFC cards by providing real-time dashboard monitoring and daily status reports. Furthermore, the pipeline performs diagnostic automations and manifests those by signaling alerts or generating Jira issues in situations where the system needs to undergo repairs [6].

In this implementation, as shown in Fig. 1, the Analysis device receives through the Batch-Ingestion relevant BLM-settings that are stored in the LSA and LAYOUT databases [7, 8]. Those include serial numbers of the electronics as well as the physical location and connectivity information of the CFC cards. From the BLM system, the Analysis device ingests, every second, temperature readings of the TC cards as well as 12 types of cumulative error counts evaluating the state of the CFC-TC connections. The BLM system reserves only 16 bits to express those errors and thus overflows are a common occurrence. The main focus of the analysis device is to detect overflows in the received counts, correct them and compute the number of new errors that have just occurred as well as the total count of errors starting from midnight of the current day. The device publishes both cumulative and new errors at a frequency of 1 Hz to the Diagnostics device. As shown in Fig. 2, those incrementing cumulative errors are also displayed in dashboards [9]. Finally, an event driven publication occurs daily at midnight, sending to the Reporting device data that are later displayed in the daily reports of the system. This entails the daily total of errors as well as the time series of temperature readings and cumulative errors. The daily total errors are loaded and stored in NXCALS. Relevant metadata from the BLM-settings are also passed along to the Diagnostics and Reporting devices.

The BLM system publishes raw diagnostic information, such as indicators signaling the beam extraction, which are consumed by the BL-ARMA Diagnostics device. The module decodes the content or absence of this information to establish a general status of the crates housing the TC cards such as ON, OFFLINE, or FAULT in the case that a beam

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Crate	CFC-A Location	CFC-B Location	Comparissons				Errors				Lost			
			D1:8		D9:16		D1:8		D9:16		D1:8		D9:16	
			CRC	FID	CRC	FID	LFA	LFB	LFA	LFB	LFA	LFB	LFA	LFB
05.L.1	BLECF.12L1	BLECF.13L1	0	0	0	0	7	0	0	0	266	0	0	0
01.R.1	BLECF.01RR17.1.7	BLECF.01RR17.1.9	0	0	0	0	0	0	0	0	4	0	0	0
02.R.1	BLECF.01RR17.1.10	BLECF.01RR17.2.2	0	0	0	0	0	0	0	0	1	11	0	0

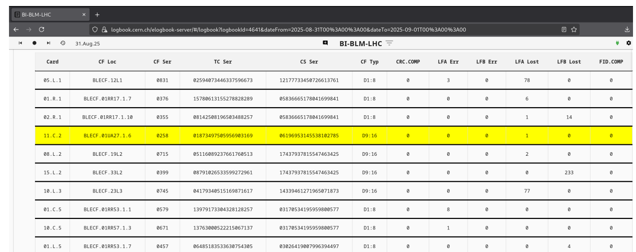
Figure 2: Web-based dashboard displaying error counts in real time.

extraction has been requested. In the latter case the module will perform diagnostics on the new error counts received from the Analysis device for further investigation. It will narrow down the root cause to one of 10 standard faults which can cause a beam extraction due to a CFC-TC connectivity issue. The root cause along with metadata such as physical locations and serial identification numbers of the cards involved are serialized into JSONs [10]. Similarly, serialized into JSON format are incidents linked to high cumulative error counts that could potentially lead to a loss of redundancy along a CFC-TC communication link. The JSON packages are sent via an event-triggered publication at midnight to the Reporting device, which in turn will generate the Jira tickets. General communication status information is displayed in real time dashboards as shown in Fig. 3.

Crate	State	Fault	Warning
SR1_BLMC	on	None	All good
SR1_BLMR	on	None	All good
SR1_BLML	on	None	All good
SR2_BLMC	on	None	All good
SR2_BLMR	on	None	All good
SR2_BLML	on	None	All good
SR2_BLMI	on	None	All good

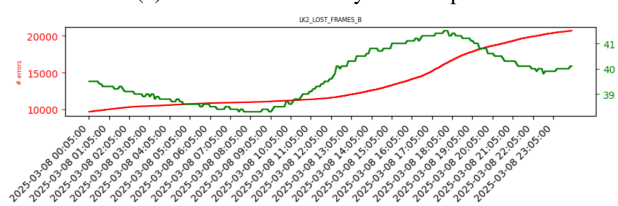
Figure 3: Web-based dashboard displaying general communication status in real time.

The Reporting device renders the information received by the Analysis module into daily status summaries that are added automatically to a designated web-based logbook. These reports include tables of the daily connectivity error counts accompanied by the physical locations and serial identification numbers of the related cards as in Fig. 4(a). Also included in the summaries are the plots illustrated in Fig. 4(b) that display the evolution of temperature of the surface electronics and the increase of connectivity errors. Additional plots displaying a 30-day summary of the daily error counts related to each CFC card are also present. The publication of such logbook entries is accomplished using the elog actor. The JSON packages sent by the Diagnostics device are de-serialized and converted into Jira issues. This process begins through transmitting via the UCAP email actor a specially formatted email directed to a designated handler within the Jira environment. Once the email is received, a custom JEMH script, specifically associated with the relevant Jira project, is activated and parses the contents of the email generating multiple tickets containing all the relevant information [11]. Lastly, the email actor is also employed by the Reporting device in order to send email alerts to the pipeline maintainer in case of missing data packages from the Analysis or Diagnostics devices.


BI-BLM-LHC
logbook.cern.ch/elogbook-server/#/logbook?logbookId=4641&dateFrom=2025-08-31T00%3A00%3A00&dateTo=2025-09-01T00%3A00%3A00
31.Aug.25 BI-BLM-LHC

Card	CF Loc	CF Ser	TC Ser	CS Ser	CF Typ	CRC.COMP	LFA Err	LFB Err	LFA Lost	LFB Lost	FID.COMP
05.L.1	BLECF.12L1	0831	02594073446337596673	12177733450726613761	D1:8	0	3	0	78	0	0
01.R.1	BLECF.01RR17.1.7	0376	15780613155278828289	05836665178041699841	D1:8	0	0	0	6	0	0
02.R.1	BLECF.01RR17.1.10	0355	08142508196503488257	05836665178041699841	D1:8	0	0	0	1	14	0
11.C.2	BLECF.01UA27.1.6	0258	01873497505956903169	06196953145538102785	D9:16	0	0	0	1	0	0
08.L.2	BLECF.19L2	0715	05116089237661760513	17437937815547463425	D9:16	0	0	0	2	0	0
15.L.2	BLECF.33L2	0399	08791026533599272961	17437937815547463425	D9:16	0	0	0	0	233	0
10.L.3	BLECF.23L3	0745	04179340515169871617	14339461271965071873	D9:16	0	0	0	77	0	0
01.C.5	BLECF.01RR53.1.1	0579	13979173304328128257	03170534195959800577	D1:8	0	8	0	0	0	0
10.C.5	BLECF.01RR57.1.3	0671	13763000522215067137	03170534195959800577	D1:8	0	1	0	0	0	0
01.L.5	BLECF.01RR53.1.7	0457	06485183533630754305	03026419007996394497	D1:8	0	0	0	0	4	0

(a) Error counts in daily status report.



(b) Temperature and error count signals in daily status report.

Figure 4: Information present in the daily status report in the web-hosted logbook.

CONCLUSION AND FUTURE WORK

A modular and fault tolerant streaming data pipeline coined BL-ARMA was presented. BL-ARMA performs monitoring and diagnostic operations on the BLM system. An implementation of the pipeline on the surveillance of the CFC-TC communication status demonstrates real-time monitoring on web-based dashboards, daily status reports on a web-hosted logbook, as well as diagnostics and issue tracking automations. Future work envisions the incorporation of additional processing units to the existing streaming pipeline, facilitated by the modular architecture of BL-ARMA. One such future update involves the introduction of a machine learning (ML) module. Such a device can grant the streaming pipeline prognostic capabilities that could forewarn the experts of an imminent fault. Furthermore, BL-ARMA pipelines can be applied to many more areas of the BLM system that are currently monitored via the older batch ETL pipeline that limits its surveillance to daily status reports that are shared to the experts via emails.

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