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SPARK ACTIVITY MONITORING FOR LHC BEAM DUMP SYSTEM

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Abstract

LHC Beam Dump System is composed of 25 fast-pulsed magnets per beam to extract and dilute the beam onto an external absorber block. Each magnet is powered by a high-voltage generator that discharges the energy stored in capacitors into the magnet by using high-voltage switches. These switches are housed in air in cabinets which are not dust-protected. In the past years of LHC operation, we noticed electrical sparks on the high-voltage switches due to the release of accumulated charges on the surfaces of the insulators and the switches. These sparks can potentially cause a self-trigger of the generators yielding to asynchronous dumps which should be avoided as much as possible. In order to detect dangerous spark activity in the generators before a self-trigger occurs, a Spark Activity Monitoring (SAM) system was developed. SAM consists of 50 detection and acquisition systems deployed at the level of each high-voltage generator and one external global surveillance process. The detection and acquisition systems are based on digitisers to detect and capture spark waveforms coming from current pick-ups placed in various electrical paths inside each generator. The global surveillance process collects data from all the acquisition systems in order to assess the risk of self-trigger based on the detected sparks' amplitude and rate. This paper describes the architecture, implementation, optimisation, deployment and operational experience of the SAM system.

INTRODUCTION

The LHC Beam Dump System (LBDS) plays a critical role in LHC machine protection, by ensuring the safe extraction of the beam from the LHC. The beam is directed to the extraction channel through the beam-synchronised activation of 15 extraction kicker magnets (MKD). Subsequently, the beam is diluted by 4 horizontal (MKBH) and 6 vertical dilution magnets (MKBV) before reaching the beam dump absorber (TDE). To accommodate the rising edge of the MKD magnetic field, a particle-free Beam Abort Gap (BAG) of approximately 3 µs is meticulously maintained within the LHC [1].

High-Voltage Pulse Generators

High-voltage pulse generators (HVPG) are used to generate the current pulse in the MKD and MKBs. The HVPGs consist of capacitors and fast high-voltage switches to discharge the energy stored in the capacitor into the magnet (see Fig. 1). The capacitor charge depends on the LHC beam energy. The conduction of high-voltage switches is started by power trigger modules (PTM) [2].

These HVPGs can self-trigger for different reasons which can result in the MKD rising edge occurring outside of the BAG, and the beam circulating in LHC might be spread over the machine aperture, which could yield damage to various machine elements. [3].

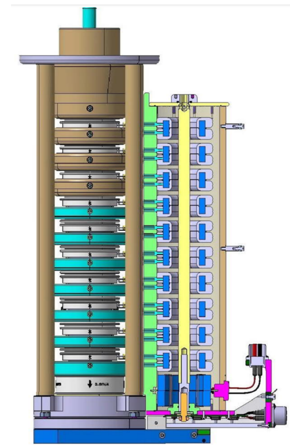

Figure 1: High-Voltage Switch used in HVPG.

Re-Trigger System

To limit the impact of a self-trigger of an MKD HVPG, a re-triggering system is implemented to trigger as fast as possible all other MKD HVPG. To this extent, re-trigger boxes (RTB) are installed on each generator, interconnected using re-trigger lines (RTL). The re-trigger boxes are connected on one side to sensors inside the HVPG to generate a pulse on the re-trigger lines in case of HV switch conduction, and on the other side to the PTM to trig conduction of HV switch in case pulses are present on the re-trigger line. [4] These sensors are installed on different power circuits of the HVPG to detect small current flows and capacitor voltage changes.

Spark Activity in HVPG

In the past years of LHC operation, HVPG self-trigger events occurred. The current waveform captured from the HVPG indicated a sign of high-voltage sparks a few µs before the start of the conduction of the high-voltage switch. Before starting of LHC operation, we manually checked for the high-voltage spark activity by using oscilloscopes on-site. This has been a time-consuming operation and it was impossible to monitor all generators continuously. To detect dangerous high-voltage spark activity before a self-trigger occurs, we decided to develop a continuous spark activity monitoring system.

SAM ANALYSERS

Spark Waveform Acquisition

SAM waveform acquisition and analysis is implemented using the Internal Post Operation Check (IPOC) framework

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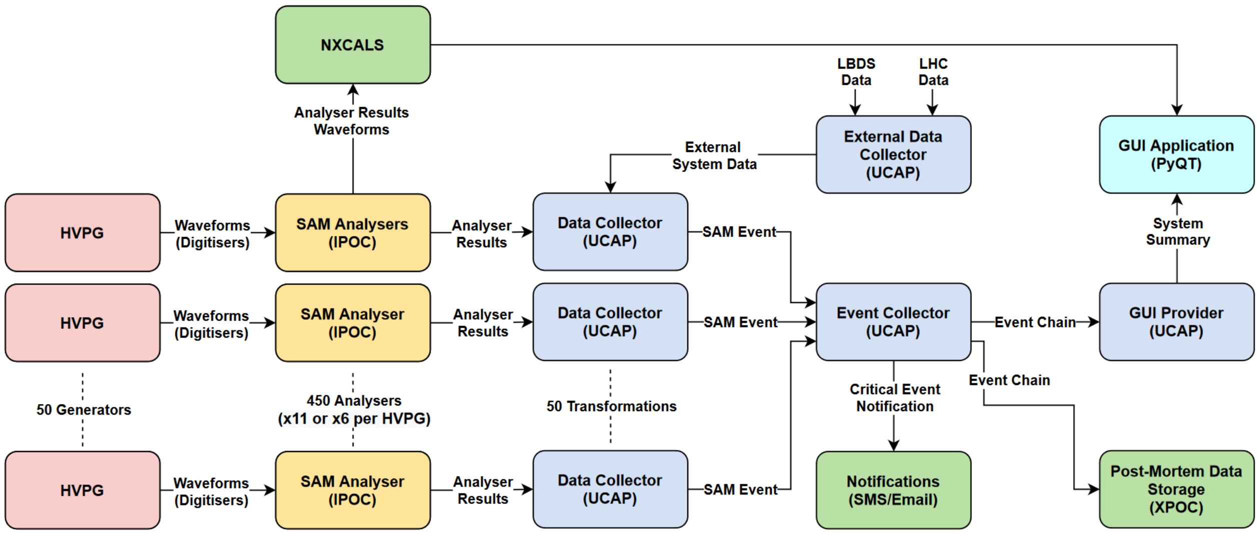

Figure 2: Main components of SAM system and data flow between them.

[5]. IPOC is a software framework to acquire and analyse waveforms by using digitisers installed on computers on-site. A total of 450 digitiser channels across LBDS are monitored by SAM, 11 for each MKD generator, and 6 for each MKB generator. These channels are connected to the aforementioned sensors inside the HVPG as well as the re-trigger lines and the PTM outputs.

The digitisers are configured as an "OR" trigger across channels. When the voltage level on a channel passes the configured threshold, all other SAM channels on the generator capture data at the same moment. The trigger threshold is set to a level just above the noise on the channels to capture and analyse the smallest possible signals. Subsequently, each acquired waveform undergoes processing on the FEC by IPOC-based analyzers to determine important characteristics of the acquired waveforms.

Spark Waveform Analysis

The analysers for each channel measure the key characteristics of the captured waveform such as the amplitude, maximum and minimum points, and the voltage level at the trigger moment. Then based on these measurements, the analyser determines if there is any activity on the analysed channel or not.

All the waveforms and the analysis results from all channels are then published on the CERN Controls Middleware (CMW) [6] and logged onto the Next CERN Accelerator Logging Service (NXCALS) [7] to be able to reload this data at later stages.

SYSTEM-WIDE ANALYSIS

A system-wide data analysis software has been developed to collect and analyze SAM activities. This software is developed using the Unified Controls Acquisition and Processing (UCAP) framework [8]. Within UCAP, users can implement transformers to collect data from other devices on CMW, process the collected data and publish outputs. Furthermore, these transformations can be linked in a chain pattern to build a multi-layered data processing architecture. The objective of collecting the data on a system-wide analyser is to identify and categorise activities with different characteristics by combining spark waveform analysis results from all generators as well as the relative external data. The main components of the system-wide analysis structure can be seen in Fig. 2.

External Data Collector

This UCAP transformation is responsible for collecting context data related to the spark events such as the accelerator mode (e.g. injection, ramp-up, flat-top, and ramp-down), beam energy and associated HVPG control values such as the capacitor voltage and control mode of LBDS. The data collected is made available for the other UCAP transformations on the system.

Data Collector

Within the SAM UCAP structure, each generator is associated with a data transformer (Data Collector) responsible for gathering analyser results from all SAM analysers on each generator. The data collector is the first link in the data analysis chain which acquires the analyser results from the SAM analysers. There is one instance of data collector for each generator. Following the acquisition of the SAM analyser results, the data collector augments the dataset with the collected external system data unifying them to form a singular "SAM Event." Each SAM event is then categorised by the data collector based on collected data, such as the first triggered channel, the maximum amplitude and the total number of channels exhibiting activity.

Each data collector is also tasked with calculating and publishing statistics for each generator, indicating metrics such as the count of events within different time windows.

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Following the categorisation, both SAM events and corresponding statistics are published.

Event Collector

SAM events, published by data collectors, are gathered by dedicated transformations (Event Collector) for each beam. These transformations aggregate all SAM events into one "Event Chain" and group events occurring within the same time window into a "SAM Activity." Each SAM activity corresponds to an occurrence featuring one or more SAM events and incorporates information such as the number of affected generators and characteristics of each acquired waveform, such as the maximum amplitude.

Using timestamps, event types, and maximum amplitudes of events occurring simultaneously, the event collector determines the source point of the activity across the system and assesses its severity. Periodically, the event collector publishes the results of this collection as a compact system summary data (Event Chain).

There are certain cases defined as "critical events":

High Amplitude Event If the maximum amplitude of the acquisition on any channel surpasses the configured "major event" threshold, the SAM system notifies experts on the notification list.

High Rate of Minor Events If the number of minor activities during the last hour or fill surpasses a configured threshold, the SAM system notifies and logs the events.

Propagated Event If the number of affected generators during a SAM activity exceeds a specified threshold, the SAM system notifies experts and logs the activity on the Logbook.

State Alarm If one of the SAM analyzers is not in a valid state for the next acquisition, the SAM system intervenes automatically, attempting to "re-arm" the analyzer. If unsuccessful, the SAM system notifies experts for manual intervention.

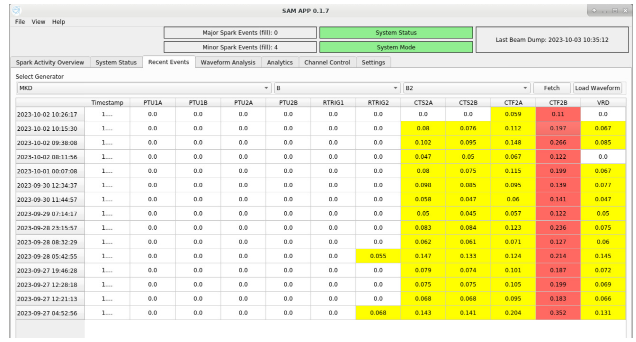
The event collector is configured to send email and/or SMS notifications to experts and log critical events into the CERN Logbook when a critical event is detected.

GUI Provider

GUI provider is the transformation responsible for reformatting the event chain data coming from the event collector transformation for efficient transfer and visualisation on the GUI application.

Post-Mortem Data Writing

After each beam dump, the SAM event chain data for the last LHC fill, created by event collector devices on each beam, is sent to post-mortem data storage. An External Post Operation Check (XPOC) [9] analyzer is being developed to process this data to detect if there are any severe events over a certain amplitude threshold or certain rate. If an event is classified as severe, the SAM XPOC analysis module can block the next fill after a beam dump, requiring expert confirmation to unblock operations. This precaution is essential as severe events may indicate a risk of self-trigger, necessitating expert review before starting the next LHC filling.



	Timestamp	PTU1A	PTU1B	PTU2A	PTU2B	RTRIG1	RTRIG2	CTS2A	CTS2B	CTF2A	CTF2B	VRD
2023-10-02 10:26:17	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.059	0.11	0.0
2023-10-02 10:15:30	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.08	0.076	0.112	0.197	0.067
2023-10-02 09:38:08	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.102	0.095	0.148	0.266	0.085
2023-10-02 08:11:56	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.047	0.05	0.067	0.122	0.0
2023-10-01 00:07:08	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.08	0.075	0.115	0.199	0.067
2023-09-30 12:34:37	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.098	0.085	0.095	0.139	0.077
2023-09-30 11:44:57	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.058	0.047	0.06	0.141	0.047
2023-09-29 07:14:17	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.045	0.057	0.122	0.05
2023-09-28 23:15:57	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.083	0.084	0.123	0.236	0.075
2023-09-28 08:32:29	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.062	0.061	0.071	0.127	0.06
2023-09-28 05:42:55	1....	0.0	0.0	0.0	0.0	0.0	0.055	0.147	0.133	0.124	0.214	0.145
2023-09-27 19:46:28	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.079	0.074	0.101	0.187	0.072
2023-09-27 12:28:18	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.075	0.075	0.105	0.199	0.069
2023-09-27 12:21:13	1....	0.0	0.0	0.0	0.0	0.0	0.0	0.068	0.068	0.095	0.183	0.066
2023-09-27 04:52:56	1....	0.0	0.0	0.0	0.0	0.0	0.068	0.143	0.141	0.204	0.352	0.131

Figure 3: A list of recent minor SAM events on an MKD generator with the source and affected channels detected.

GUI APPLICATION

The UCAP analysis layer organizes results for efficient transfer and publication on the CMW for the expert application. The application presents data including the number of spark events, the status and mode of SAM analyzers, recent events on selected generators, a list of all events since SAM system installation (historical data), and waveforms of selected events. The recent events tab of the application provides an event on each row and the amplitude of activity on each column while marking the source channel of the shown event(see Fig. 3).

Data Extractions, Caching, and Visualization

The application enables experts to visualize SAM activities or events using extracted historical data (see Fig. 4). This data can be filtered by various parameters and grouped to create distributions over maximum amplitude, generator type, source generator, source channel, accelerator energy, and time. The tool's flexibility empowers experts to generate comprehensive reports, identifying potential risks correlated to various domains. All waveforms and past events extracted from NXCALS are cached, ensuring quick access on subsequent retrievals.

FIRST EXPERIENCE RESULTS

LHC MKBH Self-Trigger Events

In September 2023, an MKB HVPG on LHC beam 2 (B2) self-triggered. But, no activity prior to the event was recorded on this HVPG. On the other hand, the total number of minor activities on neighbouring MKB HVPG exceeded the warning level, but no self-triggers occurred on this HVPG.

This event shows that the correlation between an elevated number of minor sparking in an HVPG and a self-trigger can be weaker than expected.

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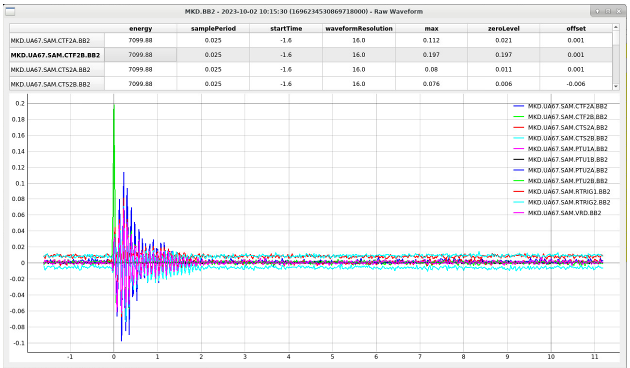

Figure 4: A minor spark waveform extracted from NXCALS by the expert application.

Captured Noise Examples by SAM

The initial acquisition trigger threshold of the digitisers is very low to capture the smallest possible activities. The system captures noise from unknown external sources. The noise amplitudes are clearly not sufficient to trigger any of the generators, no risk of asynchronous dump was identified. After some investigation, the experts identified two external noise sources:

Capturing Noise During Dump of Other Beam This, caused SAM to capture noise on MKB generators when the generators on the other beam were triggered. After the inspection of this behaviour, the acquisition trigger threshold is increased to avoid capturing frequent false activities.

Capturing Noise When the LHC Tunnel Lights are Turned On The SAM system captures noise when the LHC tunnel lights are activated. We intend to find the exact dynamics of the coupling of the noise and find a good mitigation to the problem if possible.

SUMMARY

In order to monitor the sparking activity on LBDS, a hundred digitisers were deployed. It was not possible to process the data collected from 450 channels manually and continuously, which led us to develop a centralised data processing system and a GUI application for system observation and detailed analysis. Up to this point, the SAM system helped us to identify different dynamics affecting LBDS and it keeps collecting more data and insights to enable us to build a definitive prevention system in the future.

The spark detection and waveform acquisition system is very sensitive. As a result, the SAM system captures noise signals which are not caused by real sparks but due to external system activities. Therefore, categorization and filtering of the data are very important to extract useful information from the large amount of data collected. This will help distinguish such events from other activities that may represent genuine threats.

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