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AUTOMATED ANALYSIS OF THE PROMPT RADIATION LEVELS IN THE CERN ACCELERATOR COMPLEX

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Abstract

The CERN injector complex is essential in providing high-energy beams to various experiments and to the world's largest accelerator, the Large Hadron Collider (LHC). Beam losses linked to the operation of both the LHC and its injectors result in a mixed radiation field which, through both cumulative and single-event effects poses a threat to exposed electronic equipment. Therefore, detailed knowledge of the radiation distribution and evolution is necessary in order to implement adequate Radiation to Electronics (R2E) mitigation and prevention measures, resulting in an improvement in the efficiency and availability of the accelerators. In this study, we present the automated analysis scheme put in place to efficiently process and visualise the radiation data produced by various radiation monitors, distributed at the four largest CERN accelerators, namely the Proton Synchrotron Booster (PSB), Proton Synchrotron (PS), Super Proton Synchrotron (SPS), and the LHC, where proton beams are accelerated gradually from 160 MeV up to 7 TeV.

INTRODUCTION

In high energy and high intensity particle accelerators, even during nominal operation small amounts of beam are lost, leading to a mixed-field radiation, that can negatively impact the exposed electronic systems both through the stochastic Single Event Effects (SEE) and cumulative lifetime effects, such as Total Ionizing Dose (TID) and Displacement Damage (DD).

Additionally, in regions with relatively high losses, the residual radiation levels (caused by nuclear interactions induced by the prompt radiation) lead to additional Radiation Protection limitations, such as personnel access restrictions.

Therefore, a key preventive measure is the active monitoring of the prompt radiation levels in particle accelerators to i) understand the origin of beam loss mechanism, ii) forecast the future evolution, iii) detect discrepancies from the forecasted behaviour and iv) perform mitigation actions to reduce the impact, primarly on electronics. For our analysis, the four largest CERN accelerators, namely Proton Synchrotron Booster (PSB) [1], Proton Synchrotron (PS) [2], Super Proton Synchrotron (SPS) [3] and the Large Hadron Collider (LHC) [4] are considered. They are equipment with multiple radiation monitors, complimentary to each other. Primarily, the Beam Loss Monitors (BLMs) [5] provide very good time resolution (below 1 s, depending on the accelerator), whereas Distributed Optical Fibre Radiation Sensors (DOFRS) [6] allow to measure TID levels with a good spatial resolution (1 m). Finally, in selected locations, the dedicated Radiation to Electronics (R2E) monitors, RadMons [7], are deployed, to characterise the mixed field radiation not only in terms of TID, but also the fluence values relevant to radiation effects and damage.

These monitors generate relatively large amounts (over 100 GB/day) of complex and varying data, that require state-of-the-art data engineering solutions for efficient data processing and analysis. This ensures that a comprehensive insight, based on all avaliable radiation monitors, is provided instantaneously, allowing potential mitigation actions to be planned and executed effectively.

In this paper we give an overview of the radiation monitoring and the implemented automated analysis solutions that are used within the CERN's R2E project, established to reduce the impact of the radiation on the electronic systems installed in the CERN accelerators.

PROMPT RADIATION MONITORING

Beam Loss Monitors

The core of the Beam Loss Monitoring system are the Beam Loss Monitors (BLMs), ionisation chambers filled with nitrogen, that in addition to its main purpose, i.e. machine protection, can be successfully used for dosimetry. Their main advantage is a very good time resolution that, depending on the accelerator, can be as low as few μs. The system allows to measure the TID levels in terms of energy deposited in nitrogen. PSB, PS and LHC are equipped with the same generation of the ionization chambers, whereas in the SPS older detectors are used.

DOFRS

As of 2021, PSB, PS and SPS are entirely covered by the DOFRS radiation monitor, allowing to retrieve the TID (in silica) profile along the accelerator with a very good spatial resolution (as compared with point-wise measurements by BLMs), in the order of 1 m. In case of the LHC, as of 2022, there is a partial coverage of the accelerator, in the Dispersion Suppressor regions of Interaction Points 1,5 and 7. DOFRS system provides a time evolution of the levels, however, with the significantly lower time resolution as compared to the BLM. Therefore, the synergy of both monitor types is essential to build a comprehensive picture of TID levels in terms of spatial distribution (DOFRS) and their detailed time evolution (BLMs).

RadMons

In addition to BLMs and DOFRS monitors, in the CERN accelerators there are dedicated R2E detectors, RadMons,

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that have been deployed to characterise the environment not only in terms of TID (in silica), but also the fluencies [8]: i) 1-MeV-Si-n-eq ii) HEH-eq and iii) th-n-eq.

AUTOMATED RADIATION ANALYSIS

Devices and equipment related to the accelerators' operation log data to the Next Accelerator Logging Service (NXCALS) [9], successor of the old Oracle-based CALS service. This includes the BLM, RadMon and DOFRS systems. One of the main advantages of NXCALS, is the extraction API build on top of Apache Spark [10], a unified open-source analytics engine for big data, allowing to perform studies on a dedicated cluster.

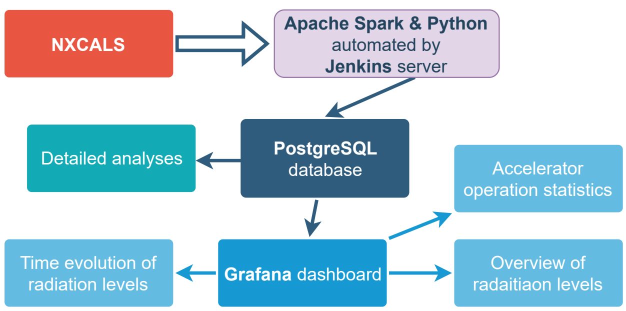

Figure 1: Scheme of the data pipeline put in place to automate the radiation data analysis.

The R2E analysis tools, schematically depicted in Fig. 1, are designed to profit from the available Apache Spark engine for the efficient radiation data processing. First, the scripts perform transformations of the data such that they can be used for dosimetry purposes, an example of which is the baseline subtraction, particularly important in low radiation regions, that compensates for systematic error caused by the digitalization of analogue signals and related nonzero value of the TID despite lack of the radiation. Later, for each monitor type and each of the accelerators, a transformed data is aggregated (e.g. integrated, time averaged) to compress the data size, while preserving the information level relevant for R2E applications. For each of the accelerator and each monitor type, a dedicated script was developed, profiting from the efficient Python libraries (PySpark, Pandas [11], Numpy [12]). The scripts are executed periodically by a Jenkins automation server, presented in Fig. 2, on the Apache Spark cluster (included in NXCALS) consisting of several thousands of CPU cores. Whenever possible, the algorithms were designed to profit from the parallelized execution offered by the Apache Spark.

The computed R2E relevant quantities, together with several statistics (e.g. peak dose rate with the time of occurrence) are then saved to a dedicated SQL database. The PostgreSQL Relational Database Management System, together with an efficient database design, provides a good starting point for further analyses as the necessary radiation data can be retrieved with maximally reduced latency. The example of later, is the R2E radiation levels dashboard [13], depicted in Fig. 3. It has been built based on the open source

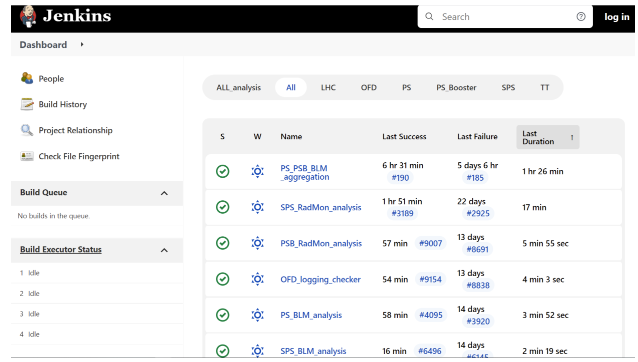

Figure 2: Main page of the Jenkins automation server that executes scripts covering various machines.

Grafana [14], with the goal of providing a global overview of prompt radiation levels across CERN's accelerator complex, as measured by all avaliable radiation monitors. Profiting from the aggregation functionality of SQL, the dashboard offers basic analytics capabilities, such as time filtering or insights from the time evolution. More customed analyses, can be easily performed thanks to the SQL API avaliable in the majority of programming languages, for example in Python.

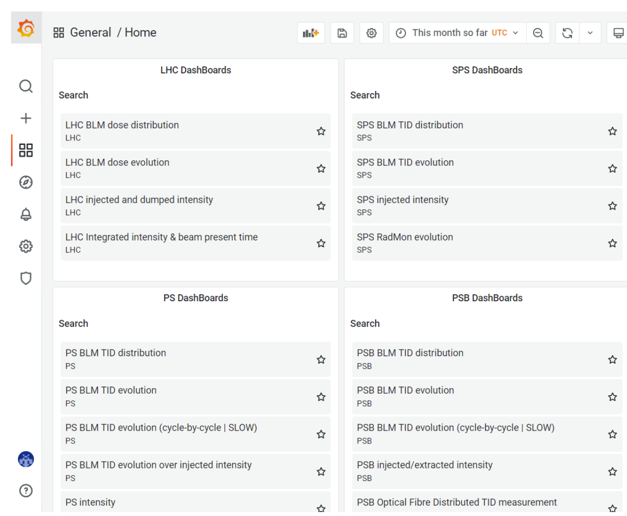

Figure 3: Home page of the Grafana based R2E dashboard used for a quick radiation levels assessment, both in terms of spatial distribution and their time evolution.

PROCESSING AND USE CASES HIGHLIGHTS

Intensity Statistics

Through the R2E dashboard, it is very straightforward to visualise selected accelerator statistics, for example injected intensities. The injected number of protons (ion contribution in terms of injected intensity is negligible) in the 2021 for the accelerators is listed in Table 1. Apart from the LHC, which was operated for 2 weeks with pilot beams only, in 2021 (post Long-Shutdown 2 recommissioning) the injected

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intensities for PSB, PS and SPS were approximately 60% of what was injected in 2018.

Table 1: Total injected proton intensities in the PSB, PS, SPS and the LHC, as retrieved from the R2E dashboard for 2021

Accelerator	2018 (10^{19} charges)	2021 (10^{19} charges)
PSB	19.20	11.93
PS	5.02	2.94
SPS	1.95	1.17
LHC	0.015	$2{\cdot}10^{-7}$

Cycle-by-cycle BLM Offset Correction

An accurate offset correction is one of the key steps during the BLM data processing, particularly relevant while using the monitors for dosimetry purposes. It allows compensating for the nonzero expected value of the signal without the prompt radiation presence (e.g. due to ADC characteristics). It is calculated on a monitor-by-monitor and cycle-by-cycle basis (for PSB, PS and LHC). An example of a PS cycle, with highlighted time period used for an offset calculation, is depicted in Fig. 4.

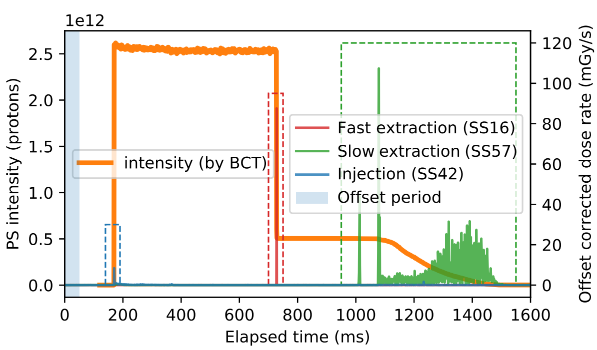

Figure 4: An example of a PS cycle with the beam intensity measurement and selected, offset-corrected, BLM signals for monitors at injection, fast extraction and slow extraction Straight Sections (SS). First 50 ms of each cycle (before the beam injection) is used to shift the signal such that the averaged value without a beam would be ≈ 0 Gy.

For example, in 2021, in the Straight Section (SS) 72 of the PS the measured offset-corrected-TID was 7.1 Gy, whereas without the offset correction the calculated value would be a factor 2.4 larger (16.8 Gy). This step is especially important for low radiation zones, where the dose rate signal to noise ratio is low, for example in the LHC arc sections [15, 16]. For instance, in 2018 in the 26th cell at the left side of the LHC Point 1, the BLMs measured approximately 50 mGy, whereas without offset correction the calculated value would be overestimated by a factor 56 (2.9 Gy).

Evolution of TID Over Time

To estimate future radiation levels and promptly react to all unexpected increases, the automated tools are designed to easily retrieve the information of the levels' time evolution, nearly in real-time. To compensate for interruptions and different modes of accelerator operation, the TID/HEH-eq evolution is often analysed with respect to the injected intensity, as in the first approximation (preserved parameters and settings of the accelerator), the radiation levels are expected to increase linearly with respect to the injected intensity. Figure 5 depicts the TID as measured by two BLMs and RadMon in the region of beam extraction from the PS towards the East Area (EA) experiments in 2021 and 2022 as a function of the injected intensity targeted for EA experiments.

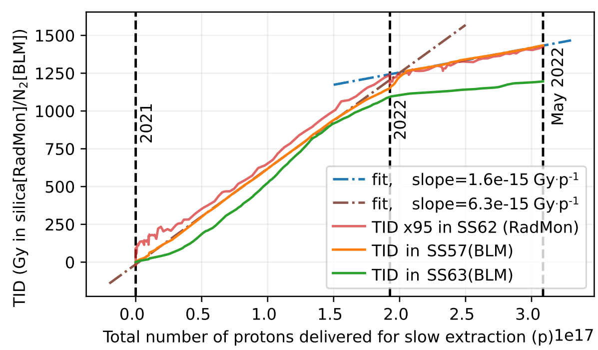

Figure 5: Evolution of the TID over the injected intensity targeted for experiments in the EA, as measured by BLMs in the Straight Section (SS) 57 and SS 63 of PS. Additionally, TID measurements by a nearby RadMon (different transverse position with respect to the BLMs) are depicted. For visualisation purposes, they were multiplied by a factor 95. For both RadMon in SS 62 and BLM in SS 57, the measured and normalized TID levels are lower by a factor 3.9, whereas for BLM in SS 63, the improvement is by a factor 8.6.

CONCLUSIONS

The presented automated analysis of the prompt radiation levels is the core system used within the R2E project for radiation data analysis. Taking advantage of multiple complementary radiation monitors (BLM, RadMon and DOFRS) deployed in the CERN accelerator complex, we are able to provide a very complete picture of the radiation levels along the accelerators, relevant not only for R2E applications but also for the accelerator operation. However, these monitors produce large volumes of data, (more than 100 GB per day), and to fully exploit their capabilities state-of-art data engineering solutions (based on Apache Spark, PostgreSQL and Grafana dashboard) were designed, implemented and are presented in this paper. The achieved efficient and automated data processing is a key to the effective radiation data exploration, allowing for prompt mitigation measure implementation in case unforeseen prompt levels are observed.

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