

# ACCELERATOR FAULT HANDLING AT SLS 2.0

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## *Abstract*

With the transition from machine commissioning to beam-line commissioning and user operation, long-term reliability and high availability of the Swiss light source (SLS) 2.0 accelerator complex at the Paul Scherrer Institute (PSI) have become critical. Rapid, systematic fault handling is essential to minimize downtime and protect the accelerator. This contribution presents the architecture and implementation of key systems developed for fault management at SLS 2.0, including the post-mortem framework, Injection Guard, and controlled emergency beam-dump procedure. The post-mortem system captures and logs comprehensive fault data to support root-cause identification, confirmation of a successful emergency beam dump and continuous improvement. The Injection Guard ensures safe and reliable injection by monitoring critical parameters and preventing injection when safety thresholds are violated. For severe fault scenarios, a controlled emergency beam dump using a fast beam dump controller (BDC), a fast beam dump magnet and a dedicated beam dump protects sensitive components such as the vacuum chamber. Together, these measures form an integrated approach to fault handling that enhances operational robustness and user reliability. Initial experience during early user operation demonstrates their effectiveness and lays the foundation for further optimization and long-term reliability.

## INTRODUCTION

The SLS 2.0 design [1] introduced two new key aspects for the machine protection in comparison to SLS-1: the risk of permanent magnet demagnetization from accumulated radiation dose [2] and the risk of machine damage from uncontrolled beam losses. The latter became clear during the project phase of SLS 2.0 when simulations of the loss distribution for coasting beams indicated highly localized energy deposition at devices such as an in-vacuum insertion device (ID) and a superconducting superbend. In addition, following uncontrolled beam losses, the risk of vacuum leaks due to the increased energy density of the low-emittance beam and the thin 1 mm copper vacuum chamber [3] and even thinner 0.5 mm steel vacuum chamber for the corrector magnets is significant. Especially in light of experience from other facilities [4–6] these circumstances gave the necessary motivation to develop a dedicated beam abort system enabling fast and controlled beam energy deposition for minimized risk. The SLS-1 RF phase inversion beam abort technique was no longer viable. The key ingredients for the new beam abort system are the fast BDC, a dedicated beam dump kicker (BDK) and a dedicated beam dump [7]. An

overview of the SLS 2.0 machine protection system and initial commissioning [8,9] experience was presented in [10]. This contribution focuses on the fault handling aspects and further gained experience with the SLS 2.0 machine protection system.

## INJECTION GUARD

The injection guard is the initial machine protection layer with the goal of preventing misinjected beams and defusing critical situations that could potentially lead to beam aborts. In contrast to the alarm handler which requires the operator to take action, the injection guard directly enforces a safe machine state by itself. It inhibits the distribution of injection triggers by the timing master and thus the injection of additional charge or dangerous misfiring of the pulsed magnets (e.g., one of the kickers out of the 4-kicker bump fails). The injection guard is a high level application implemented in python and running as a systemd process on a dedicated high level application server. The injection guard monitors the state of critical accelerator subsystems and beam parameters. Monitored systems include vacuum pressure (static limits, detection of abrupt pressure increase), pulsed magnets (status ok and setpoint within nominal operating range), magnets, beam abort system, machine interlock system (MIS), vacuum control system (VCS), radio frequency (RF) and ID gaps. Monitored beam parameters include lifetime, transmission, orbit, tune, total and single bunch charge. The interlock thresholds must be lower than the corresponding beam abort thresholds since many of the monitored systems such as the beam position monitor (BPM) [11] system or the filling pattern feedback (FPFB) [12] will directly request a beam abort when their respective thresholds are surpassed.

## BEAM ABORT SYSTEM

When critical machine thresholds are surpassed and risk to the machine is imminent, the beam abort system is activated: When one of the systems connected to the in-house developed compactPCI serial (CPCI-S) [13] based fast BDC [10] hardware detects one of its monitored signals leaving the safe operating range it requests a beam abort. Within less than 1  $\mu$ s, the fast BDC triggers the distribution of post-mortem and beam dump events to enable other accelerator systems to trigger the acquisition of post-mortem data or enter a safe state for the imminent beam abort, i.e., the main RF [3, 14] prepares for the fast increase of reflected power by reducing forward power and the 4-kicker-bump is inhibited to avoid overlap with the opposing deflection from the BDK. A recent feature upgrade of the BDC has been the addition of a new feature on the firmware (FW) level: synchronization of

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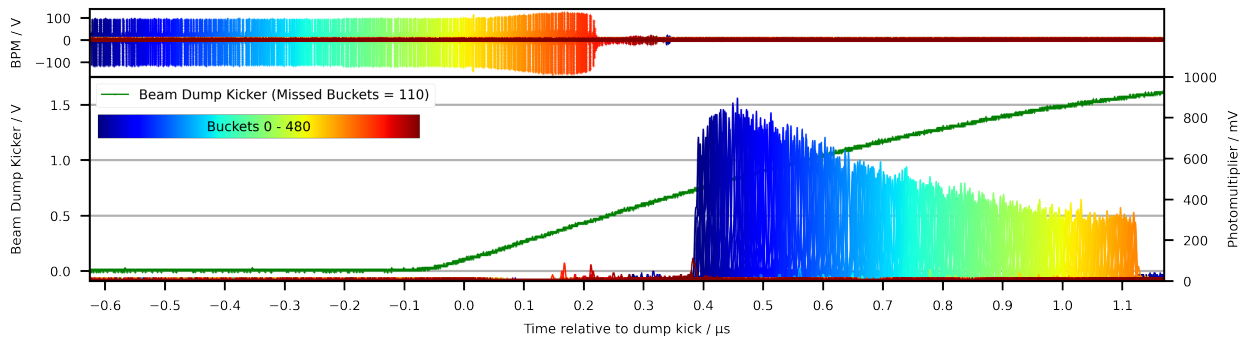


Figure 1: Post-mortem measurement recorded with a 1 GHz bandwidth digitizer triggered by the beam dump event. The upper plot shows the bunch-by-bunch filling pattern measured at a beam position monitor. The lower plot shows the beam-dump kicker current amplitude (green) together with the signal from a Cherenkov loss-monitor fiber installed near the dedicated beam dump, confirming controlled and safe beam deflection of 77.1 % out of 480 bunches or 82.2 % out of 450 bunches (nominal filling pattern) to the dump. The latter requires synchronization of the beam abort to the filling pattern.

the BDC with the revolution trigger enabling alignment of the BDK pulse with the filling pattern gap. This enables increasing the fraction of stored beam reliably deflected to the dedicated beam dump to 83 % for our nominal filling pattern with a 30-bucket ion-clearing gap (harmonic number is 480). The fraction of stored beam distributed to any safe location, i.e., the dedicated beam dump, the thick and thin septum and the horizontal collimators can be optimized to about 100 % (Fig. 2). Another upgrade on the beam abort system on the fast, strong and reliable/resilient BDK was the shift to using factory-encapsulated fast thyristor switches enabling stable operation at higher switching voltage than the previously used in-house encapsulated switches which suffered from higher leakage currents and breakdown at lower voltages.

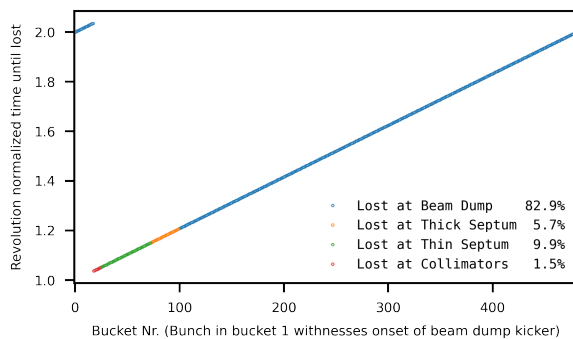


Figure 2: Tracking simulation of the beam-abort loss distribution for the nominal SLS 2.0 beam abort. Bucket 1 corresponds to the bunch witnessing the onset of the beam dump kicker. The first bunches encountering the onset of the beam dump kicker receive a second kick after one revolution and are then deflected to the dedicated beam dump. Subsequent bunches experience increasing deflection and are safely intercepted along the ring circumference, starting at the horizontal collimators in straights 9 and 5. In total, 98.5 % of all bunches are deposited directly downstream of the beam dump kicker, at the thin and thick septum with the majority (82.9 %) deflected to the dedicated beam dump.

This has enabled us to reliably operate all four stages of the BDK at design parameters, i.e., to safely dump the beam, we use the rising slope of a damped sine wave current with period of 6.7  $\mu$ s and amplitude value 7 kA, corresponding to a deflection of 12 mrad.

## POST-MORTEM

Besides the extremely helpful alarm lists from the BDC and other programmable logic controller (PLC) safety systems (e.g., MIS, VCS) the backbone of the SLS 2.0 post-mortem system are multiple high and low level post-mortem buffers enabling the reliable acquisition of post-mortem data for each beam abort event: High level post-mortem buffers are realized using experimental physics and industrial control system (EPICS) [15] circular buffer records for 10 Hz monitoring of post-mortem relevant measurements, i.e., radiation-sensing field-effect transistors (RadFETs), beam current, lifetime, beam size, vacuum pressure, filling pattern, RF frequency and power. Low Level post-mortem buffers are available for the Libera beam loss monitors (BLMs) [16, 17], BPM turn-by-turn (TbT) data [18], RF System, Pulsed Magnets. In addition we have setup dedicated post-mortem diagnostics for performance evaluation of the beam abort itself: a 1 GHz band width (BW), EPICS-integrated fast digitizer triggered by the BDC measures the sum signal from the four individual stages of the BDK, the bunch-by-bunch signal from a dedicated filling pattern measurement BPM and the photomultiplier-based Cherenkov radiation detector registering photons from loss-monitoring fibers placed in the vicinity of the beam dump. This system has proven extremely useful to confirm controlled beam aborts motivating us to extend this measurement to other expected loss hot spots, i.e., thin and thick septum and horizontal collimators in straights 5 and 9. In this way we will be able to monitor directly the controlled deposition of almost all bunches in the train, making it possible to further optimize the synchronization of the BDK with the gap in the filling pattern (Fig. 1). The post-mortem is acquired and processed for viewing with the help of several dedicated applications: The RF post-mortem

application gathers cavity-related data and enables plotting of the data sets against each other in any combination. The general post-mortem application structures the rest of the acquired data into an automatically created electronic log-book (ELOG) entry. The latter triggers an email notification to the machine experts and the expert group of the system that requested the beam abort and creates an hdf5 file with all the gathered post-mortem data.

## ROOT CAUSE AND FAILURE ANALYSIS

Following each beam abort the machine experts check the post-mortem ELOG entry to confirm that the beam was dumped in a safe manner. For each beam abort all beam dump requests received within the first 42 s are sorted in a list according to their arrival time measured with an accuracy of 10 ns so one can immediately find which system requested the beam dump, helping subsequent identification of the root cause for the beam abort. In parallel RF experts check the RF post-mortem data for hints of RF failures such as arcs at the couplers or amplitude/phase errors in the feedback loops. In case of uncontrolled, critical or unclear beam aborts these are followed up on during the next machine development meeting which is usually attended by all relevant experts. Here the root cause and indicated consequences such as, e.g., optimization of interlock limits, adjusting of operation parameters (e.g., beam current, filling pattern, insertion device gap limits), increased vacuum scrubbing efforts or introduction/adjustment of operational procedures (e.g., closing of photon shutters after opening ID gaps) are discussed.

## SUMMARY

The two different levels of implemented machine protection systems, namely high level (injection guard, post-mortem service) and low level (BDC, MIS, VCS, PM buffers of RF, BPMs and BLMs) and their ground up design approach for integrating post-mortem diagnostics have proven extremely useful. Root cause identification for most beam aborts is straightforward and correctly documented in the ELOG entry by the automated post-mortem service. The beam abort system has been further optimized and in the meantime reliably and safely dumps 83 % of the stored beam to the dedicated beam dump. For the future it is planned to further improve the monitoring of loss hot spots for beam aborts and to optimize the filling pattern synchronization of the BDK and improve the automated post processing / analysis of post-mortem data.

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