CHARACTERIZATION OF BEAM LOSS AT MAX IV IN-VACUUM INSERTION DEVICES

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Abstract

Four Libera Beam Loss Monitors (BLMs) were installed downstream of four consecutive in-vacuum undulators (IVU) at the MAX IV 3 GeV storage ring in order to survey beam losses under various operational conditions. The BLMs are operating in counting mode, with the loss-detection threshold defined from measurements taken without a stored beam. The BLMs were configured to provide stable, high-dynamic-range loss detection.

We performed a series of controlled studies to compare the loss signatures produced by different operational events, such as scraping down the beam, sudden beam dumps, full beam injections, and regular top-up cycles. The measurements show that scrape-downs generate the highest localized loss rates, while sudden beam dumps produce almost no detectable signal at the BLM locations. Top-up injections exhibit consistent and repeatable loss patterns, providing a useful benchmark for routine operation. All events were studied with insertion device gaps both closed and open; a significant decrease in detected losses was observed when the gaps were opened.

These results provide a baseline for understanding the local loss behavior downstream of the IVUs and will also provide more refined future operational procedures.

INTRODUCTION

The MAX IV Laboratory in Lund, Sweden, operates the world's first operational multi-bend achromat (MBA) storage ring, providing ultra-low electron beam emittance and extremely high X-ray brilliance [1]. The 3 GeV storage ring hosts ten insertion devices of which six are in-vacuum undulators. These devices provide high photon flux and brightness by operating with very small magnetic gaps down to 4.5 mm (ca. 2.25 mm distance magnet-beam) [2]. The combination of small magnetic gaps and the in-vacuum design means that the undulator magnets are directly exposed to the electron beam and thus are particularly susceptible to localized beam losses that may result in demagnetization or degradation of the magnets.

Understanding beam losses near insertion devices is important for both machine protection and stable operation. Losses may occur during injection, beam dumps, orbit perturbations, or deliberate beam scraping. In IVUs, localized beam losses can deposit energy in the vacuum chamber and magnet structures, potentially leading to heating and partial demagnetization of the permanent magnets. Monitoring these losses therefore provides insight into the behavior of the stored beam and helps ensure safe operation of the insertion devices.

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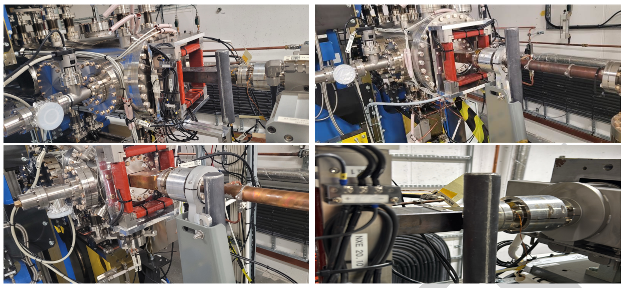

Figure 1: The four Libera BLMs mounted downstream of each observed IVU.

In this work, four beam loss monitors (BLMs) were installed at the exit point of four consecutive IVUs in the MAX IV 3 GeV storage ring. The purpose of the study is to characterize the loss signals produced by different events during operation and to establish a baseline understanding of the local loss behavior near these insertion devices.

Beam Loss Monitors

In our test set-up, we use the Libera BLM system, with detectors based on scintillators coupled to photomultiplier tubes (PMTs). The detectors are positioned close to the vacuum chamber at the insertion device exit points that serve the ForMAX, CoSAXS, BioMAX, and MicroMAX beamlines, see Fig. 1. The PMT output signal consists of unipolar pulses with negative polarity, corresponding to individual loss events [3].

The Libera BLM continuously samples the detector signal with high time resolution (8 ns) and processes it using configurable threshold logic. In counting mode, individual pulses that exceed a predefined threshold are automatically detected and counted, producing a signal in counts per unit time [4], in our set-up counts per second. We determined the thresholds from background measurements taken without a stored beam, ensuring reliable detection of both continuous and transient beam losses.

EXPERIMENTAL RESULTS

A series of experiments were performed to characterize the beam losses under different machine conditions. The study includes full injection, deliberate beam scrape-downs, and routine top-up operation. In addition, dedicated tests were carried out to evaluate the influence of RF and tune variations, as well as the effect of individual insertion device configurations. For all measurements, the BLM signals were analyzed in terms of peak loss rates and, where relevant, accumulated losses over the duration of the event. Throughout all experiments, the detectors have identical configuration settings.

Table 1: Peak loss rates LR_{peak} and accumulated loss AL for both, all insertion devices open (o) and closed (c). Units are in million counts.

IVU	$LR_{peak,o}$	AL_o	$LR_{peak,c}$	AL_c
ForMAX	0.128 1/s	57.12	0.158 1/s	52.9
CoSAXS	0.021 1/s	7.93	0.053 1/s	16.7
BioMAX	0.040 1/s	15.67	0.168 1/s	51.9
MicroMAX	0.016 1/s	6.04	0.096 1/s	30.8

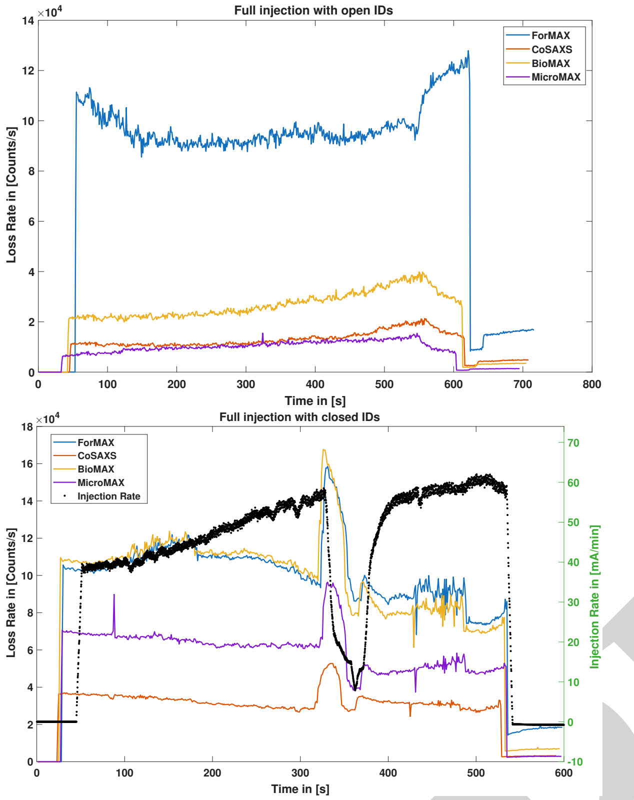

Figure 2: Beam loss signals during full injection for open (top) and closed (bottom) ID gaps, including the injection rate.

Full Injection

Beam losses during full injection from zero to nominal current at 400 mA were studied for the cases with all insertion devices open, and all closed. As a reference value, the baseline loss rates at these IVUs under nominal operation is in the order of 5×10^3 counts per second. The loss signals are displayed in Fig. 2 and summarized in Table 1.

Among the four observed insertion devices, ForMAX IVU exhibits a pronounced loss rate during injection with fully open ID gaps, while loss rates at the other IVUs stay comparatively low. In this instance, the injection rate was stable at 40 mA min^{-1}. We can exclude mounting differences of the detectors and their distances to the beam pipe are consistent. Our current hypothesis is that the difference is a consequence of the ring acceptance and the dynamic aperture during injection.

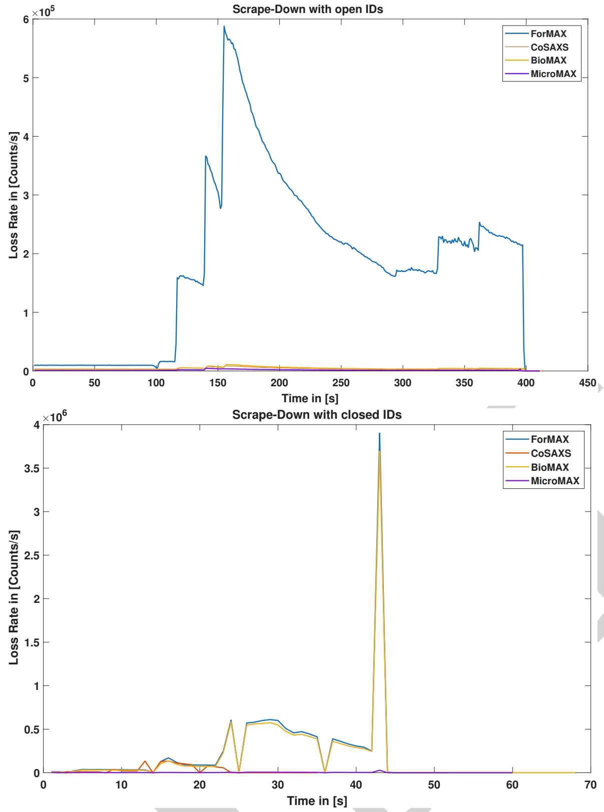

Figure 3: Beam loss signals during beam scrape-down for open (top) and closed (bottom) ID gaps.

During full beam injection with closed ID gaps, the loss rates increase other insertion devices as well. While ForMAX IVU exhibits largely the same behavior, the loss rates at the other BLMs increase manifold, notably at the BioMAX IVU up to similar levels like at the ForMAX IVU. With ID gaps closed, the machine is fully under load. In this instance, we attribute the changes in loss rate to the ring acceptance and the dynamic aperture. The accelerator has no beam collimation system that blocks halo particles. Additionally, there is no implementation of local optics compensations and thus, no compensations of beta-beats. The tune feedback is a global feedback system in the ring. The connection to the ring acceptance can be seen in the injection rate. Beam losses with closed IDs reduce while the injection rate improves. During our measurements, a sudden drop in injection rate occurred, while spikes in the local loss rates at the BLMs occur. This can mean that a larger portion of the injected beam was not accepted by the stored beam. The loss rates recover as soon as the injection rate improves again.

Beam Scrape-Down

Controlled beam scrape-down measurements were performed to intentionally induce beam losses and study their dependence on the ID gaps, see Fig. 3.

For open gaps, peak loss rates are relatively small in the order of 4×10^3 counts per second, with the notable exception of the BLM at the ForMAX IVU, exhibiting a peak loss rate of ca. 6×10^5 counts per second. While scraping down a beam with closed ID gaps, the loss characteristics at the ForMAX IVU remains unchanged, but the BLM at BioMAX IVU situated two achromats downstream records similarly high loss rates. It shall be noted that the scrape-down procedure with open gaps took ten times as long, as a more careful approach was chosen. This however resulted in a significantly higher total loss at the ForMAX IVU of 70 million counts versus 13 million counts when scraping down fast. It could however be that we just shifted the loss pattern along the ring. This could be tested in the future by either installing BLMs more frequently, or with supplementary Monte-Carlo simulations.

Beam Top-Ups

Beam losses during routine top-up operation and closed ID gaps were analyzed and found to be significantly lower than in all other cases studied. The loss signals are stable and reproducible across repeated injections. Typical peak loss rates during top-up are in the range of 1×10^3 to 1.5×10^4 counts per second, so only marginally larger than the typical baseline losses. With a typical duration of approximately 10 s per injection, the accumulated losses are comparatively small as well.

Influence of Individual Insertion Devices

A dedicated study was performed to investigate the influence of individual IVUs on beam losses during injection. A full 400 mA injection was split into 20 mA stacks selectively closing different combinations of ID gaps. The measurements show that beam losses are detected by all BLMs regardless of which IVU is closed. Even when a given IVU remains open, its corresponding detector records elevated loss signals during injections performed with other devices closed.

This supports the hypothesis that in our recorded losses, we are mainly dealing with effects of dynamic aperture. Although closing individual IVUs increases overall loss levels, the response of the detectors hints towards a correlation in loss patterns between different sections of the machine, but this is not yet conclusive and has to be investigated further.

Comparison of Loss Characteristics

A comparison of all experiments shows that beam scrape-downs with closed insertion device gaps produce the highest instantaneous losses, with peak values reaching approximately 4×10^6counts per second.

Full injection results in lower peak losses, up to approximately 1.7×10^5 counts per second, but contributes consistently to accumulated losses due to the longer duration of the process. In contrast, top-up injections produce the lowest losses, with peak values below approximately 1.5×10^4 counts per second and minimal accumulated losses.

Overall, scrape-downs dominate peak loss behavior, while injection processes dominate accumulated losses. Both cases, however, are heavily influenced by their duration. For injections, the main contributing factor is injection efficiency, which depends both on the ring acceptance, and the trimming of the LINAC and the transfer line. For scrape-downs, the main factor is how fast the scraper is inserted into the stored beam.

RF- and Tune Changes

Dedicated measurements were performed to investigate the influence of RF- and tune variations on beam losses. For this test, we deactivated the RF- and tune feedbacks, and varied them up to negative and positive 10 Hz and up to 1×10^{-3} in horizontal and vertical tunes. Within the resolution of the Libera BLM system, no significant changes in either peak loss rates or accumulated losses were observed for both RF adjustments and positive or negative tune shifts. The loss signals remained at baseline levels with only minor fluctuations comparable to background noise. These results indicate that RF and tune variations during nominal operations do not contribute significantly to localized beam losses downstream of the insertion devices.

CONCLUSION

Beam loss measurements downstream of the in-vacuum insertion devices in the MAX IV 3 GeV storage ring show that different operating modes produce distinct loss signatures. We analyzed and compared the loss characteristics at for different phases of operation, namely injection to full beam current, regular beam top-ups, manually scraping down the stored beam. Additionally, we observed the loss characteristics while changing the RF frequency or the working point of the machine in the absence of an active tune feedback.

Taking into account the accumulated losses, longer processes, such as injection, contribute substantially over time, whereas scrape-downs with closed gaps produce the highest instantaneous losses. These results provide a baseline understanding of loss behavior near IVUs and support the development of improved operational and machine protection strategies.

Our current hypothesis is that all of the observed loss patterns are caused by ring acceptance and dynamic aperture and beta-beat, since there is no local optics compensation scheme implemented yet.

REFERENCES

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