CASE STUDIES WITH HED-MELT, MODELING HIGH-ENERGY-DENSITY CONDITIONS IN ACCELERATORS [*]

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Abstract

The `HED-Melt` (**H**igh **E**nergy **D**ensity **M**odeling of **El**ectron Beam Impacts **T**oolkit) software suite was developed for studying the damage resulting from beam impacts in accelerators [1]. We have made additional improvements to the toolkit workflow and physics modeling, and have examined specific loss scenarios matching the operation conditions in the Advanced Photon Source Upgrade (APS-U) storage ring. Losses were observed in two operational modes, high-coupling 48-bunch timing mode (up to 140 mA) and high-coupling 216-bunch “many-bunch mode” (up to 200 mA). Data recorded during these losses and observations of collimator damage are presented and were used to improve the simulation workflow.

INTRODUCTION

The upgraded Advanced Photon Source (APS) storage ring began commissioning in April 2024 and has now been operating for two years. In this time, a significant number of fast beam losses have occurred. Five sectors contain in-board, horizontal collimators, which intercept the beam during these losses, and prevent damage to more sensitive beamline components [2]. The increased brightness of the APS-U lattice gives rise to energy densities intense enough to cause significant damage to collimators and other machine components [3]. While the collimators are designed to absorb beam impacts and can be replaced as needed, it is advantageous to minimize damage. A vertically-deflecting fan-out kicker (FOK) kicks the beam when a fast beam loss is initiated, spreading out the energy density vertically over the face of the collimator. However, we have seen a number of scenarios where steps of the fast beam abort process do not operate as designed. Additionally, we continue to see damage to collimator surfaces, requiring them to be replaced during machine maintenance shutdown periods. The beam losses seen in the upgraded storage ring provide us with the ability to study the damage to collimators as well as the effectiveness of the collimators for machine protection.

The HED-Melt framework [4] was developed to study potential High-energy density (HED) conditions in accelerators [5–8]. While the tool is useful in estimating damage to materials from beam impacts in ideal/nominal cases [1], the operational data often presents edge-cases. Previous simulation results show the benefits and limitations of the current model. We will discuss how the observations of beam losses inform our modeling and will present a method of using turn-by-turn (TBT) beam position monitor (BPM) data, collected during user operations, to simulate specific loss events. This allows HED-Melt to be used in two ways; (i) the design and planning of new machines and machine protection systems, and (ii) understanding and predicting damage in specific operational configurations. Currently, no diagnostics are in place to monitor the health of the collimators installed in the machine. The second prong is, therefore, important in prioritizing collimator access during the limited machine downtime.

APS-U OPERATIONS

The storage ring contains collimators in five non-user-serving sectors around the injection region. Each collimator is positioned near the beam axis in order to intercept the beam during losses while also minimizing the impact on beam lifetime. After a series of lifetime and dynamic aperture studies, the collimator in sector 1 was retracted fully in October 2025. Of the remaining four collimators, impacts are most frequently observed in sector 38 and damage to this collimator is the most severe. Several studies of the FOK indicated the beam was being insufficiently kicked and timing issues were seen in some beam loss events. As a result, the FOK voltage was increased, in October 2025, to provide a larger vertical deflection. To date, seven collimators have been replaced, with sector 38 being replaced between every user run. Figure 1 shows examples of two collimators damaged by beam strikes, both removed in May 2025.

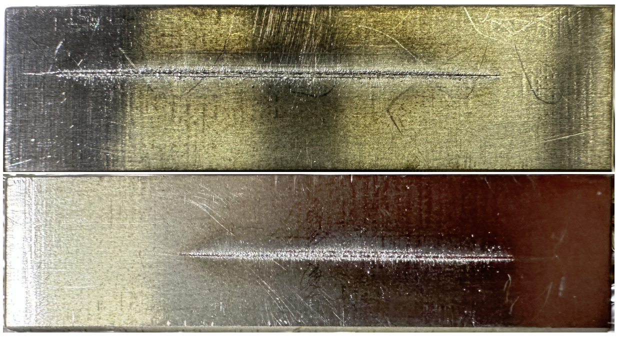

Figure 1: Photos of collimator jaws removed from sector 38 (top) and 1 (bottom) in May 2025, showing damage from beam strikes. The jaw is 14 mm tall (y) and 50 mm in length (z). Upstream is to the left.

As of the first user run of 2026, APS-U has operated in two fill patterns; (i) 216-bunch "many-bunch mode" up to

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200 mA, and (ii) 48 bunch "timing mode" up to 135 mA. Currently, both modes use a family of skew quads to strongly couple the x/y beam motion, producing a round beam. However, APS-U was also designed to operate in “brightness-mode” in which 200 mA are stored in 324 bunches with a 10 : 1 horizontal to vertical emittance ratio. In this configuration, the peak power-density of the beam may be up to four times higher. In addition, the plan is to increase charge in 48-bunch timing mode to operate at 200 mA. This emphasizes the need to understand and reduce the damage observed on the collimators in the machine’s current state.

Three-dimensional microscopy measurements were taken of the two collimators removed from sectors 1 and 38 in May 2025, producing 2-D height maps of the beam-facing surfaces. Figure 2 shows a series of profile measurements taken at different longitudinal positions along each collimator. The damage seen on the S01 collimators is narrow and deep, likely a result from a few, highly-localized beam strikes. The S38 collimator, on the other hand, shows a uniform, shallower trench which is likely caused by repeated, more diffuse beam strikes. This explanation is consistent with previous simulations of fast beam losses using the HED-Melt suite [9].

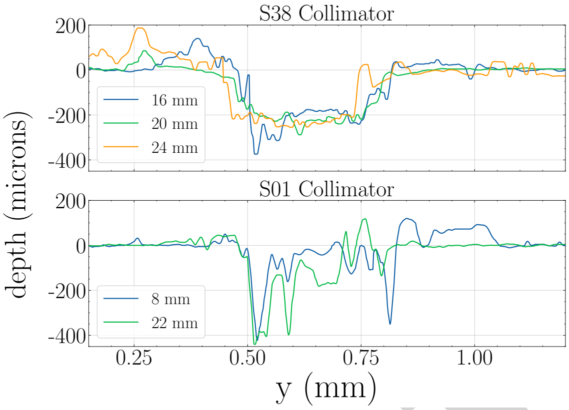

Figure 2: Surface measurements of the damaged collimators taken from sectors 38 (top) and 1 (bottom). Each trace represents the surface depth along the y-axis for different longitudinal positions.

Turn-by-turn Loss Data

The turn-by-turn (TBT) bpm data, recorded during a fast beam loss event, provide information about the beam dynamics and beam-collimator interactions during the event. These data both serve to validate the elegant tracking step of the HED-Melt suite, and to estimate the beam power absorbed by each collimator.

An example of the TBT data collected during a beam loss is shown in Fig. 3. This event likely resulted in the highest power density absorbed by the S38 collimator during the first run of 2025. The two plots show the horizontal (top) and vertical (bottom) beam centroids, normalized beam current (red), and loss rate (blue), recorded by a bpm just upstream of the S38 collimator. In this event, the peak loss occurs when the vertical centroid is near a turning point in its oscillation. The vertical centroid measured by the bpm is a full turn average of all of the bunches. Simulations show the variation in the bunch-to-bunch vertical position still causes some reduction in the energy density; however, the bunch-to-bunch variation is significantly smaller than the overall oscillation amplitude. When the loss occurs around the turning points, the energy density is higher than a loss at ±90° in the phase. Because the beam is frequently lost in a fraction of the oscillation period, the oscillation phase at the time of the loss can have a large effect on the damage.

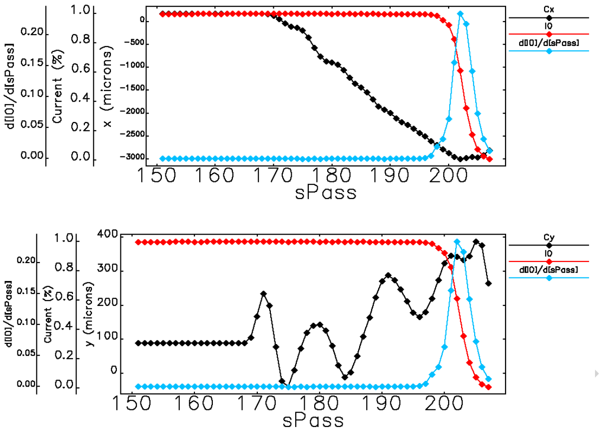

Figure 3: TBT data of beam loss occurring on March 3, 2025 from 200 mA showing the horizontal (top) and vertical (bottom) centroids, normalized beam current, and loss rate.

Collimator Damage Estimation

The collimator damage can be estimated from the TBT data with two pieces of information (i) the beam loss per sector, and (ii) the position of the vertical centroid when it strikes the collimator. With the transverse beam size, determined through elegant tracking, these can be used to estimate the profile of the power density absorbed by a collimator during a single loss event.

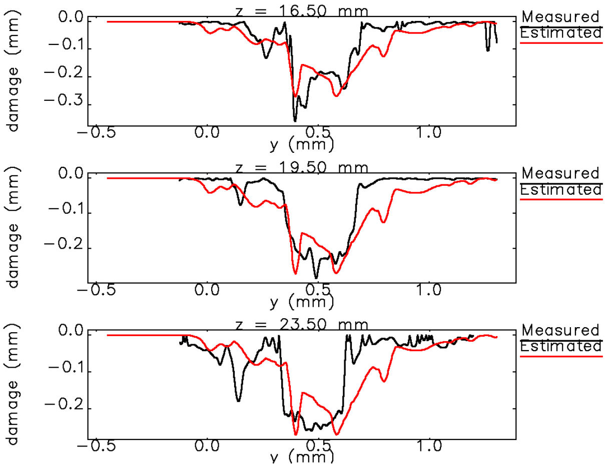

Figure 4: Surface profile measurements of damage to S38 collimator removed in May 2025 at three longitudinal positions ($z = 16.5/19.5/23.5$ mm)

Using the TBT bpm data and surface profile measurements from a previous collimator irradiation study [10, 11], the depth of the surface damage can be roughly estimated as a linear fit of the cumulative power density $d(y) = \kappa P(y)$, where κ is empirically determined with dimensions of length over power density. This simple model can predict the damage attributed to a single beam loss or the damage expected on a collimator after a full run; as shown in Fig. 4.

The damage estimated by this model roughly matches the surface measurement. However, this simple treatment ignores thermodynamics and does not account for other important machine protection considerations, such as the profile of the heat-affected-region, or any regions which melted and re-solidified. For these, we must turn to thermodynamic modeling and the HED-Melt toolkit. This analysis is best used, as a first-step, to identify specific loss events with high potential for damage, before running more robust (but computationally expensive) simulations.

HED-MELT AND OPERATIONS

The data collected during APS-U operations were used to validate and expand the HED-Melt toolkit. The TBT data, lattice optics measurements, and other machine studies were used to benchmark the elegant tracking step of the simulation suite. Additionally, the beam losses seen during operations revealed some abnormal loss cases and limitations to the current simulation workflow.

Accurately modeling the particle dynamics during a beam loss in APS-U requires full consideration of a number of effects such as, impedance and interactions between the beam and rf cavities. Measurements of the lattice optics, chromaticity, and tunes are routinely taken during operations and are used to setup the elegant model. The growth in the transverse beam distribution is largely determined the lattice coupling, chromaticity, and rms momentum spread.

Benchmarking

Studies of the FOK and lattice optics were used to benchmark and improve the elegant lattice model. A series of studies measured the bunch-by-bunch deflection of the beam by the FOK. This allowed us to better estimate the deflection amplitude of each bunch in the beam. The spread in bunch-to-bunch deflection amplitude also has an affect on the energy density absorbed by the collimator. The fan-out kicker amplitude was eventually increased in October 2025, and Fig. 5 shows the simulated versus recorded bpm data during a beam loss.

The TBT data were also used to validate other properties of the simulated lattice such as the betatron decoherence, betatron tunes, and energy loss per turn. The horizontal and vertical centroids of a simulated and real-world beam loss are presented in Figure 5. The data are recorded in a dispersive region so the horizontal centroid drifts as the beam loses energy. In the vertical plane, the amplitude and frequency of the betatron oscillations are similar. This analysis can be preformed in response to changes to the machine lattice and confirms the simulated lattice produces the expected behavior.

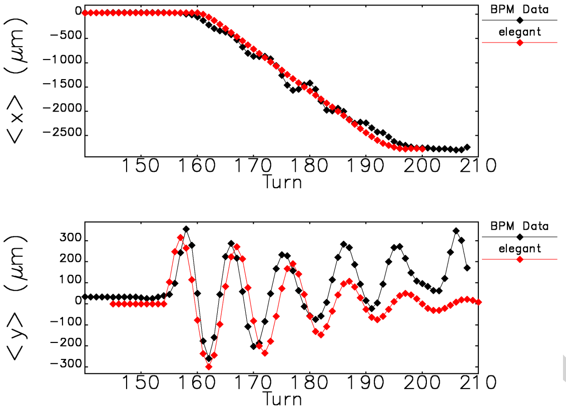

Figure 5: Turn-by-turn BPM (black) and simulated (red) x/y centroids during a beam loss event.

HED-Melt Using TBT Data

One notable observation of the operational data is that the phase of the vertical oscillation when the beam is lost has a large affect on the power density absorbed by the collimator. To account for this behavior, we implemented a method of using the TBT BPM data to simulate specific loss cases with HED-Melt.

This involves simulating the 6-D beam distribution in elegant, and tracking the evolution after the rf is muted and the FOK is fired. In this scheme, the beam distribution is output for each turn, at the location of the collimator. Then the simulated beam distribution is transformed, aligning the transverse centroid with the BPM data. It would be difficult to attempt to match the exact beam motion during a loss with modeling alone, so using the TBT data in this way, allows for better simulation of specific loss events.

DISCUSSION

Observations of beam losses during the first two years of APS-U operations provide a good benchmark for computational modeling of collimator damage. The data were used to validate and improve the particle tracking step of our simulations. They also reveal abnormal loss cases which our framework was unable to model appropriately. The improved tracking model can also be used with TBT data, recorded during beam losses, in future APS-U operations. Using the TBT data, we have developed a tool capable of simulating the thermodynamic evolution of the collimators in specific loss cases. This will aid in monitoring collimator health going forward and developing methods for reducing collimator damage.

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