14th International Beam Instrumentation Conference,Liverpool, UK JACoW Publishing
ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPMO42

MEASURING THE EFFECTS OF FAST BEAM LOSS ON THE ADVANCED PHOTON SOURCE UPGRADE STORAGE RING COLLIMATORS*

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Abstract

The Advanced Photon Source Upgrade (APS-U) storage-ring (SR) is equipped with five horizontal collimators used to intercept 6-GeV electrons during fast whole-beam aborts and protect the rest of the SR. The collimators are located in sectors 37, 38, 39, 40, and 1. A fan-out kicker (FOK) system has been installed to reduce damage to the collimators during whole-beam loss events. Since APS-U began commissioning in April 2024, dozen of these events have taken place; in most, but not all cases, the FOK system has worked properly. Turn-by-turn beam position monitors provide beam dynamics data during the loss events. However, limited diagnostics prevent in situ evaluation of the collimator beam-facing jaw surfaces. During August 2024 and January 2025 maintenance periods, some of the collimators were extracted from the vacuum chamber and examined. Faint beam strike damage was observed on the S01 collimator jaw, but more significant effects were seen on the S38 jaw. Additional examinations were conducted in May and August 2025. Measurements of beam motion during fast aborts are presented as well as microscopy images of the S38 damage. Coupled simulations results are compared with observations.

INTRODUCTION

Horizontal aluminum collimators have been placed in sectors 37, 38, 39, 40 and 01 (S37-S01) of the Advanced Photon Source Upgrade (APS-U) storage ring (SR) to intercept electrons lost via Touschek scattering, injection halo, and fast beam aborts; here we focus on the effects from fast aborts. The collimators are located in the high-dispersion region between the A:S1 sextupole and A:Q4 reversed-bend magnets in all five sectors [1, 2]. A plan view of the collimator assembly is presented in Fig. 1. The collimators play a vital role in protecting beam-facing surfaces from direct strikes during fast whole-beam loss events.

The APS-U machine protection system (MPS) receives a number of inputs employed to assess the status of the circulating 6-GeV electron beam. These inputs come from many sources including beam position limit detectors (BPLDs) beam position monitors (BPMs), rf system status indicators, and radiation monitors. Earlier experiments conducted in the former APS SR showed damage occurring in test pieces struck by beams meant to evaluate possible collimator material and geometry [2].

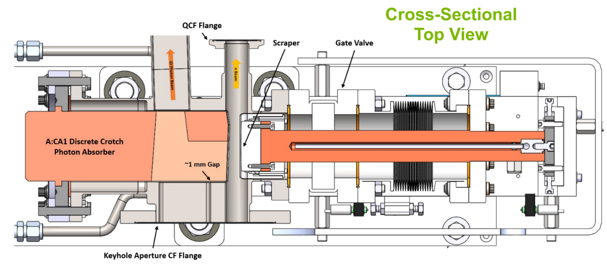

Figure 1: Plan view of the horizontal collimator assembly.

OBSERVATIONS AND MEASUREMENTS

A vertically-deflecting fan-out kicker (FOK) is designed to protect the five horizontal collimators in the APS-U storage ring (SR) during a fast beam abort [3]. The FOK does this by providing a vertical kick to the beam after a triggering event. The vertical kick lowers the power density by both "painting" the beam vertically on the surface of the collimators as well as decohering or expanding the transverse cross section, in this sense its function is similar to that of the decoherence kicker [4]. To be effective, the FOK must be triggered concurrently with the command given to mute the rf to allow sufficient time for decoherence. Measurements indicate the FOK typically triggers $\approx 7\ \mu s$ after rf muting; this is considered an acceptable delay.

Recent data collected by the data acquisition (daq) turn-by-turn (TBT) postmortem (POMO) system have shown that this sequence is not always followed. In the following section, examples are given for when the FOK is triggered properly as well as triggered late during beam loss events.

Turn-by-Turn Data

TBT BPMs provide approximately 1-second of data around fast beam loss events triggered by the MPS. The machine timing event system, designated by the initial MRF provides triggering events for many accelerator systems including the TBT BPMs as well as the FOK. The MPS sends a signal to the MRF when conditions require the stored beam to be dumped. The MRF then issues an event (104) which triggers the FOK thyratron; the resulting magnetic field bumps the bunch train vertically. The rf drive to the cavities is also muted at this time which causes the beam to spiral inboard.

* Work supported by the U.S. D.O.E.,Office of Science, Office of Basic Energy Sciences, under contract number DE-AC02- 06CH11357.
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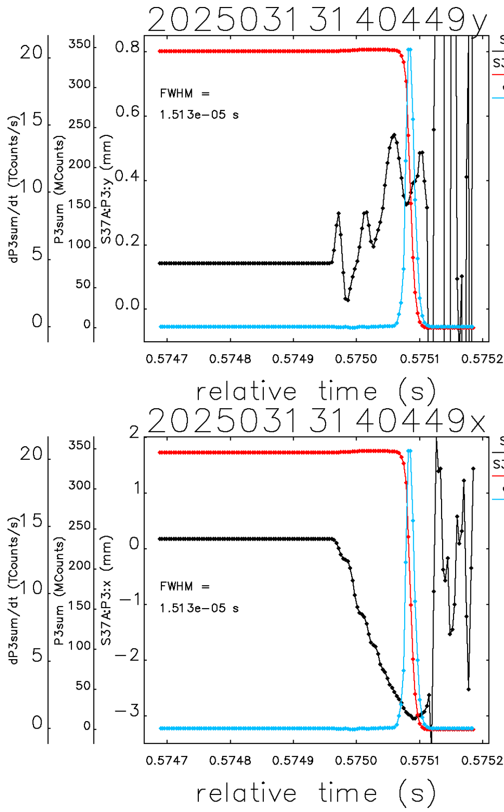

Figure 2: TBT data from the S37A:P3 BPM during a fast beam abort from 200 mA. Top: y-centroid; bottom: x-centroid. BPM sum and sum derivative are shown on both plots.

The S37A:P3 BPM, located in a high dispersion region, is used to interpret beam centroid motion. Figure 2 presents beam centroid data from a fast beam abort during 200-mA, high-coupling, 216-bunch operation. In this case, the FOK fires as expected with muting of the rf approximately 30 turns before the sum signal drops indicating a beam strike. During the 2025-2 User Run, the FOK was found to be firing significantly later that shown in Fig. 2. In these cases, a partial loss of rf drive power caused the beam to spiral inboard, exceeding a BPLD limit which then generated an MPS trip. In these situations, the FOK was triggered only a short time before beam impact as shown in Fig. 3.

Fan-Out Kicker Amplitude

The FOK concept was initially tested in the previous APS storage ring employing a ceramic chamber. A voltage setting of 2 kV generated a 245 µrad kick which was found to be sufficient to limit damage on an aluminum collimator test piece [3]. The APS-U vacuum chamber material is Inconel with a wall thickness of 0.5 mm [5]. Simulations indicated this change reduced the peak magnetic field strength within the chamber by a factor of 2.5 [6]; in addition, the pulse width increased significantly. During recent operations, the FOK voltage has been set to 1.5 kV; thus, a kick amplitude of 74 µrad was expected. Elegant simulations indicated an average vertical oscillation amplitude of 700 µrad; however, mea-

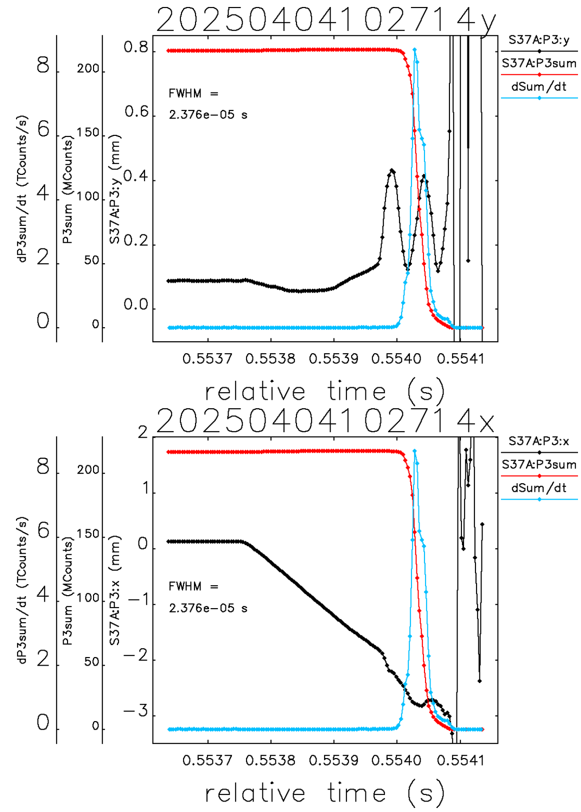

Figure 3: Loss of rf drive on one of the two klystron systems causing a BPLD MPS trip and consequently a late triggering the FOK. Top y-centroid motion; bottom: x-centroid motion.

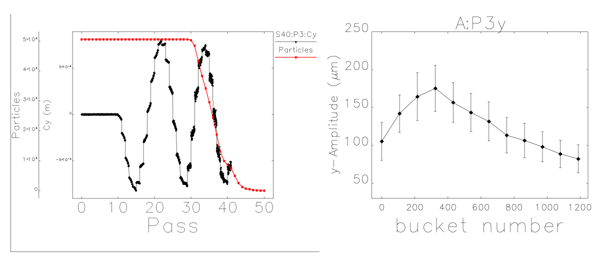

Figure 4: Left: Predicated vertical oscillation with the FOK operating at 1.5 kV. Right: Measured vertical oscillation amplitude.

surements indicated a significantly lower amplitude (Fig. 4).

Collimator Jaw Damage

Based on earlier experimental data as well as modeling, the TBT data strongly suggested that damage would be observed on collimator jaws placed closest to the beam axis. The S01 jaw is positioned closest to the chamber centerline with its apex at $x = -2.5$ mm; S38 is the next closest at $x = -3.2$ mm. An image of the S38 jaw removed during the May 2025 Maintenance period is presented in Fig. 5; damage to the surface is visible. Damage to the S01 jaw was also observed in May. An image of the impacted region is shown in Fig. 6 revealing an area of multiple strikes.

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The collimator jaws are machined with an 80-cm radius which causes the center of the jaw (apex) to stand ≈ 300 µm above the chord line that runs from the upstream to downstream ends of its 41-mm length. Using a Keyence VR-3200 microscope, surface height data on the jaw surface were obtained (Fig. 7). Significant erosion is observed along the beam strike path with void depths as great as 400 µm.

High-Energy-Density Simulations

High-Energy-Density (HED) coupled code simulations [7] were carried out to model the conditions present in the first several runs of the APS-U storage ring. These simulations used a beam current of 114 mA and looked at three cases of reduced FOK deflection (0.0 µrad, 25 µrad, and 73.6 µrad). Figure 8 shows the simulated transverse cross section at the center of the collimator material for the 25 µrad and 73.6 µrad cases. In the first case, a narrow region of material, approximately 100 µm deep, is vaporized and is surrounded by a region of melted material (orange). A significant melt region is also seen in the 73.6 µrad case. At 114 mA, these simulations correspond to roughly half of the design beam current and indicated that the observed ~ 33 µrad deflection is insufficient to prevent collimator damage.

DISCUSSION AND SUMMARY

Figure 7 indicates that void depths in the damaged region of the collimator jaw reach ~ 400 µm. Melt regions with reduced mechanical strength can extend further. APS-U SR vacuum chamber wall thickness such as the FOK chamber mentioned above are of the same scale. Thus, the collimators carry-out the important task of protecting the SR vacuum envelope. To protect the collimators, modifications to address rf/MPS triggering are underway; also increasing the FOK voltage will be tested.

ACKNOWLEDGMENTS

Thanks to R. Soliday and H. Shang for assistance with analysis scripts. Also, thanks to T. Clute and the MOM Vacuum team as well as all the AES staff involved with the removal, inspection, and replacement of the collimator jaws. Thanks to M. Jaski for providing the OPERA simulation results.

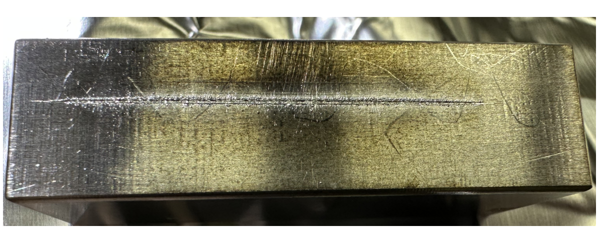

Figure 5: S38 collimator jaw beam-facing surface removed in May 2025. The jaw length is 41 mm and height 14 mm.

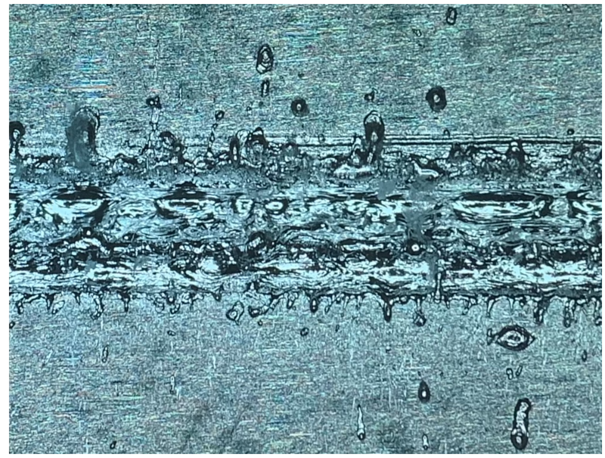

Figure 6: Microscopy image of the S01 jaw strike region. The vertical width of the strike region is 700 µm.

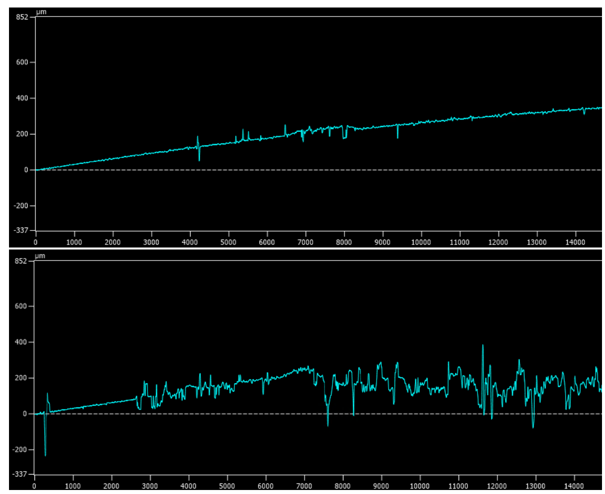

Figure 7: Surface height measured on the S38 collimator jaw extracted in May 2025 covering the upstream 14 mm. Top: adjacent to the the strike region. Bottom: through the strike region.

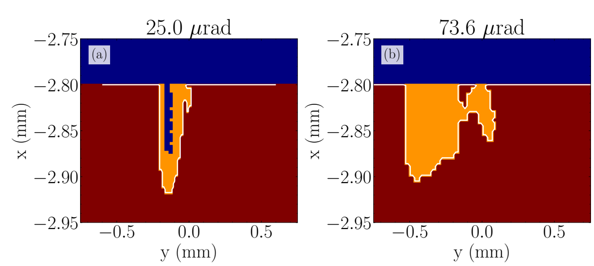

Figure 8: Simulated transverse cross-section of the collimator apex for a single beam strike showing the effect of a 25 µrad FOK deflection (a), and a 73.6 µrad kick (b).The color scale represents the phase of the material where red=solid, orange=liquid, and blue=vaporized/vacuum.

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