OPERATIONAL EXPERIENCE WITH BEAM ABORT SYSTEM FOR SUPERCONDUCTING UNDULATOR QUENCH MITIGATION*

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Abstract

A beam abort system has been implemented in the Advanced Photon Source storage ring. The abort system works in tandem with the existing machine protection system (MPS), and its purpose is to control the beam loss location and, thereby, minimize beam loss-induced quenches at the two superconducting undulators (SCUs). The abort system consists of a dedicated horizontal kicker designed to kick out all the bunches in a few turns after being triggered by MPS. The abort system concept was developed on the basis of single- and multi-particle tracking simulations using `elegant` and bench measurements of the kicker pulse. Performance of the abort system—kick amplitudes and loss distributions of all bunches—was analyzed using beam position monitor (BPM) turn histories, and agrees reasonably well with the model. Beam loss locations indicated by the BPMs are consistent with the fast fiber-optic beam loss monitor (BLM) diagnostics described elsewhere [1,2]. Operational experience with the abort system, various issues that were encountered, limitations of the system, and quench statistics are described.

INTRODUCTION

Protection against beam-loss-induced quenches is a well-known issue in high-energy proton accelerators that use superconducting magnets. Superconducting wigglers and SCUs employed at synchrotron light sources have quench-detection interlocks to protect the magnet; however, characterizing and mitigating beam-loss-induced quenches is reported only at APS [3] and Canadian Light Source [4]. At APS, both SCUs were found to quench sometimes during beam dumps triggered by the Machine Protection (MPS) or Personnel Safety (PSS) Systems, with ID6 SCU (a.k.a. SCU0 [5]) quenching more often than ID1 SCU (a.k.a. SCU1) (SCUs are powered off prior to manual beam dumps). Quenches can occur when less than 1 nC is lost in the coils, which is less than 0.3% of the total stored beam. The beam is lost mostly on the smallest aperture, which is the 5-mm gap insertion device ID4 vacuum chamber, but beam losses are also clearly observed at the SCU locations [1,2]. For both SCUs, quench recovery is typically fast enough to allow them to be operated once the beam is restored; however, such quenches are best minimized.

In January 2016, a new beam abort system was implemented at APS that works in tandem with the existing beam dump system. Its purpose is to control the beam loss location away from the IDs and SCUs and, thereby, minimize beam loss-induced quenches. The abort system consists of a dedicated horizontal kicker that stays charged during user operation, and its discharge is triggered by MPS. Should the abort kicker fail to fire, MPS would dump the beam as usual. Using a peak kick ≥ 1 mrad, the entire beam is lost on the chamber walls within a few turns. The design loss location is the injection straight section (Sector 39) vacuum chamber [6].

ABORT KICKER

The abort kicker (AK) design was described previously [3], and is based on the APS injection kickers. In order to kick out the entire beam, the kicker pulse waveform must be sufficiently long. Figure 1 shows the free-wheeling diode that was added to stretch the pulse.

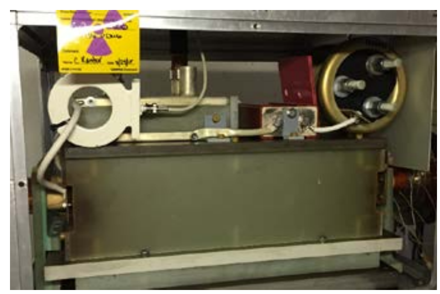

Figure 1: Photo showing free-wheeling diode added to stretch the abort kicker pulse.

The kicker waveform was determined experimentally by recording the motion of a single bunch whose position relative to the 0th rf bucket (i.e., fixed reference on the pulse waveform) was scanned in steps of 108 buckets (corresponding to every other bunch in a 24-bunch fill pattern). For every measurement, the kick amplitude was determined by comparing the measured trajectory with simulation. A significant complication is beam position monitor (BPM) saturation for trajectories greater than 5 mm, whereas the peak trajectory for a kicker voltage setpoint of 10 kV (corresponding to a peak kick of 1.3 mrad) is 10 mm—this is close to the requirement for beam abort, as discussed in the next section. Therefore, the fit was based on trajectories less than 5 mm, where the measured and simulated trajectories agree well. The kicker waveform extends over several turns, so where possible the kicks on three consecutive turns was extracted.

Figure 2 shows the measured kicker profile. On this plot, one turn corresponds to 24 bunches. This plot also shows the waveform obtained in the bench measurements of the

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kicker that were performed before installation. A long coil was used to measure the integrated magnetic field, from which the kick angle was computed.

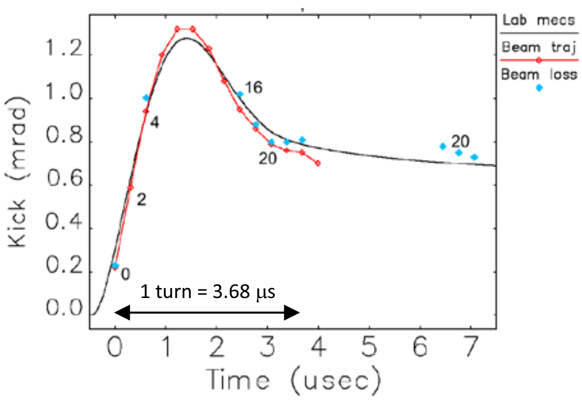

Figure 2: Abort kicker waveform (10 kV setpoint) measured using the beam trajectory (red symbols) and its comparison to the lab measurement. Beam loss is discussed in the beam tests section.

LAYOUT AND TRACKING

The abort system concept was designed on the basis of multi-particle tracking simulations using `elegant` [7]. The standard model lattice was used, which gives tunes of (36.2, 19.3) and chromaticities of (4.0, 6.4) (i.e., operations without transverse feedback.) Each bunch was modelled using 2000 macroparticles with Gaussian 6D distributions (3σ cutoff) and tracked for three turns. For each bunch, the kicker waveform was sampled at the appropriate time (bunch index) on the first, second, and third turns, and a kick was applied to the particles accordingly. Tracking included x-y coupling by adding the normal and skew quadrupole parameters from the calibrated lattice model.

The kicker location is fixed due to available space in the Sector 36 (S36) straight section (shared with four rf cavities). The kick amplitude was chosen to target the injection straight section (S39) vacuum chamber as the beam loss location. Since there is no abort gap, a number of bunches on the leading edge of the kicker pulse always survive the first turn, and must get a sufficient kick on the following turns to be dumped into S39. In addition, the amplitude of the bunches that survive the first turn must be small at the SCU locations, otherwise there is a risk of losing significant beam there.

Figure 3 shows the simulated centroid trajectories of 24 uniformly-spaced bunches in the first turn, using a peak kick of 1 mrad. About 96% of the beam is lost in S39 in two turns. Note the small trajectories at the locations of SCU0 and SCU1 on the first turn.

BEAM TESTS

Machine studies with the abort kicker initially gave beam losses in ID1 sufficient to cause SCU1 to quench (but not SCU0). After calibrated sextupoles and the SCU1 photon absorber (PA) 17-mm aperture were included in the simulations, then beam losses simulated in ID1 and ID6 were more consistent with the studies result. The calibrated sextupoles correspond to chromaticities of (1.9, 1.9) (i.e., operations with transverse feedback).

It turns out the phase advance of orbits of individual bunches varied for the two simulated sets of sextupoles, especially on the second turn. Figure 4 shows this effect, which was more pronounced at ID1.

The new simulations showed that bunches lost outside of S39 correspond to kick amplitudes between 0.7 and 1 mrad (see Fig. 2); this issue was first described in [3]. The simulated loss locations were reproduced well for nearly all the bunches using measured BPM turn histories (sum). The undesired beam losses can be avoided by moving the beam closer to the S39 inboard wall before firing the kicker. The present method of dumping the beam during an MPS trip is to interrupt the rf amplifier drive for 100 ms, which causes the beam to move towards the chamber wall as the rf field decays and the beam loses energy to synchrotron radiation. Simulations showed that the fraction of beam losses at ID1 and ID6 was significantly reduced for an energy offset of about -1.5%. The solution, therefore, was to delay the abort kicker pulse relative to the MPS trigger.

Studies were carried out with different values of the abort kick and delay. The calibrated BLM loss charge at ID1 and ID6 (average of two and four fiber bundles, respectively) are summarized in Table 1 for the different conditions. Figure 5 shows the beam energy for the different conditions, measured as an average orbit position at the BPMs. Without the abort kicker, the beam is lost on the wall after about 175 μs (50 turns). The BLM signals were strongly reduced for a kicker setpoint of 10 kV and a delay of 60 μs, and further reduced by an order of magnitude for a delay of 90 μs (25 turns). With the longer

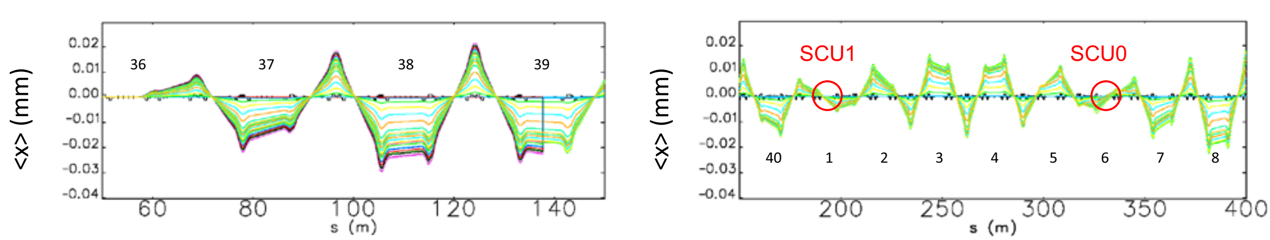

Figure 3: Simulated beam trajectories for 24 bunches and kicker voltage setpoint of 8 kV (1.0 mrad peak kick), showing about one third of the first turn after the kick. The abort kicker is located in S36 and the target loss location is S39. The sector straight sections are labelled.

delay, it was confirmed that the SCUs did not quench when energized to typical operating values. A kicker setpoint of 8 kV showed somewhat higher BLM losses, even though simulations showed no losses. In all cases, the losses at ID6 are < 1 nC, which is consistent with quench prevention [1,2]. Unlike ID1, the ID6 SCU photon absorber does not intercept aborted-beam losses, and the abort system protects ID6 SCU with or without the delay.

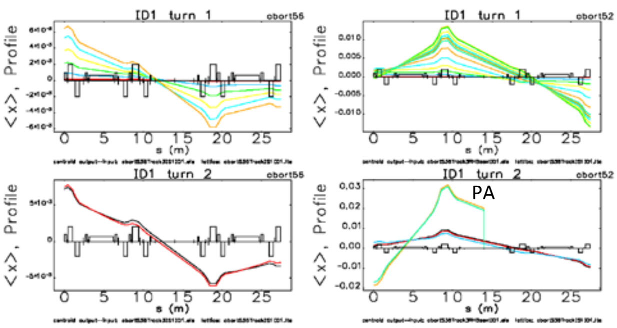

Figure 4: Simulated bunch trajectories at the ID1 straight section, showing first turns on the top and second turns on the bottom. Left is high and right is low chromaticity. Note the vertical scales differ on the panels (units: mm).

Table 1: ID1 and ID6 BLM calibrated loss charge (Q) vs. abort kick and delay (100 mA beam).

Conditions	ID1 Q (nC)	ID6 Q (nC)
0 kV, 0 delay	11.5	0.29
10 kV, 60 µs	0.33	0.060
10 kV, 90 µs *	0.044	0.0028
8 kV, 90 µs	0.56	0.54

* SCUs energized; no quench detected.

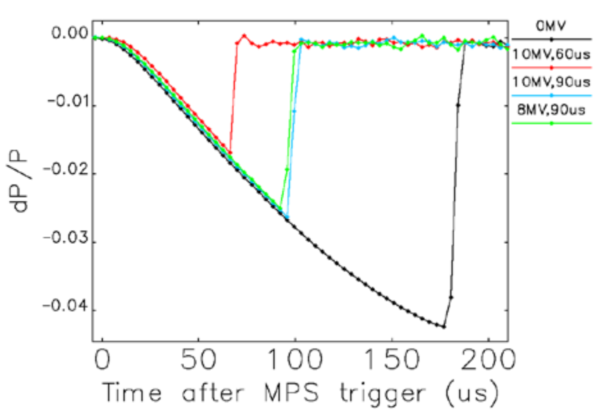

Figure 5: Beam energy as a function of time after MPS trigger event. The moment of beam loss corresponds to the energy reverting to zero.

OTHER ISSUES AND LIMITATIONS

Two other issues were observed in testing the abort system. First, trips were observed in the S38 rf cavity waveguide arc detector. It was postulated that the trips were due to the arc detector fiber optic (FO) signal cable intercepting the beam loss shower. Simulations showed that a 10-kV kick causes beam losses at the S38B:Q2 quadrupole just upstream of the S38 rf section. A test arc detector was installed outside the tunnel, with a FO signal cable placed inside the tunnel parallel to the real one, but not connected to the waveguide. Investigations showed that the real arc detector did not trip when firing AK without beam. Therefore, discharge-induced noise was ruled out. The real and test arc detectors both tripped when firing AK with beam. This is consistent with beam losses at S38B:Q2 rather than an arc inside the waveguide. We found a configuration that avoids rf trips but that gives small losses at ID1 and ID6: lower the AK setpoint to 9 kV and keep the 90-µs trigger delay.

The second issue is a limitation of the beam abort system that occurs when the beam is dumped by PSS. In this case, the dipole is turned off in addition to the rf, and both ID1 and ID6 BLMs detect beam losses before MPS senses beam centroid motion [1]. The cause for these early losses is under investigation. The abort kicker is ineffective for PSS dumps because beam is lost before the kicker is triggered. We accept this situation since PSS dumps are typically a rare occurrence. Most beam dumps are triggered by MPS, with only about ~10% being triggered by PSS.

OPERATIONS AND STATISTICS

The abort system has worked reliably so far. As designed, the kicker remains charged during user operations and discharges consistently on MPS events. Between January and August 2016, the **SCU0 quench rate decreased dramatically from 80% to 14%** of beam dumps, while the **SCU1 quench rate remained about the same**: 23% of beam dumps before and **19%** after. There was an unusually high rate of PSS-related dumps during first three months of 2016 – 40% of all dumps – and the abort kicker system is ineffective with PSS beam dumps, as stated above. Overall, the beam abort system is effective in mitigating SCU quenches 80-85% of the time. Of the 15-20% of beam dumps where an SCU quenches, 10% is attributed to the PSS rate, and 5-10% to sensitivity of the loss location to machine conditions.

ACKNOWLEDGMENTS

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