ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE066

DEVELOPMENT OF AN ABORT KICKER AT APS TO MITIGATE BEAM LOSS-INDUCED QUENCHES OF THE SUPERCONDUCTING UNDULATOR*

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Abstract

The first superconducting undulator (SCU0) at the Advanced Photon Source (APS) has been delivering 80-100 keV photons for user science since January 2013. SCU0 often quenches during beam dumps triggered by the machine protection system (MPS). SCU0 typically recovers quickly after a quench, but SCU1, a second, longer device to be installed in 2015, may take longer to recover. We tested using injection kickers as an abort system to dump the beam away from SCU0 and the planned location of SCU1. An alternate trigger was tested that fires the kickers with MPS. We demonstrated that controlling the beam dump location with kickers can significantly reduce the beam losses at SCU0, as measured by fiber optic (FO) beam loss monitors (BLMs), and can also prevent a quench. A dedicated abort kicker system has been developed based on `elegant` simulations. A spare injection kicker was modified to produce the required waveform. Injection kicker tests, simulations, and the abort kicker design are described. Demonstration of this strategy in APS has implications for the APS Upgrade, where more SCUs are planned.

EXPERIMENTAL TESTS

A superconducting undulator, SCU0, installed in APS was found to quench 80% of the time during beam dumps triggered by MPS. Simulations and beam studies suggest that beam losses > 50 pC in a small coil volume deposit energy sufficient to raise the coil temperature above the NbTi critical temperature [1,2]. Quench recovery is typically fast enough to allow SCU0 to be operated once the beam is restored. The consequences of beam-induced quenches is potentially greater for the longer device, SCU1, since it may require longer recovery time.

FO BLMs [3] were installed in Sector 6 (“ID6”) on the SCU0 vacuum chamber (warm) transitions to characterize the beam losses [2]. Horizontal injection kickers (IK) were used to test a beam abort system. The injector kicker pulse waveform is ~2 µs FWHM. In order to kick out a full turn, which is 3.68-µs long, two horizontal injection kickers were used as a pair, with the second kicker timing shifted by half a turn. We used IK1 (in Sector 38) and IK4 (in Sector 40) as a pair, and IK2 and IK3 (both in Sector 39) as another pair. The kickers were set to their maximum peak kicks of ~1.5 mrad and it was verified that the entire beam was lost. The studies were repeated for the nominal 102 mA stored in 24 and 324 uniformly-spaced bunches, two APS operating modes. In Table 1, the BLM integrated loss charge for an MPS trip is compared to that using the kickers. The results demonstrate that controlling the beam loss location with kickers can significantly reduce the beam losses at SCU0.

To test whether lower ID6 beam losses can prevent a quench, 102 mA were stored in 24 bunches and SCU0 was powered to a typical main coil current of 650 A. IK1 and IK4 were fired, dumping the entire beam, and SCU0 did not quench. In this case, the losses at SCU0 were below the BLM measurement threshold.

Table 1: Total Uncalibrated ID6 BLM Charge, Comparing MPS Beam Dumps with Injection Kickers

Dump type	24 bunches (nC)	324 bunches (nC)
MPS	444	480
IK1+IK4	1	6
IK2+IK3	30	44

BEAM ABORT SYSTEM

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. The beam is lost mostly on the smallest aperture, which is the ID4 vacuum chamber [4], but beam losses are also clearly observed at ID6 where SCU0 is installed. To control the loss location at the level required, a kicker will be employed to dump the beam away from ID chambers.

While the injection kicker tests were a successful proof of principle, the loss distribution is not ideal, in that beam is lost in ID1, the planned location of SCU1 (see Model validation). The beam abort system should limit losses at both SCU0 and SCU1. Also, injection kicker abort configurations are incompatible with top-up operation.

The new beam abort system will use a dedicated horizontal kicker in the Sector 36 rf straight section, that stays charged during user operation, and whose 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. Beam losses are mainly on the thick septum chamber in the injection straight section [5].

*Work supported by U. S. Department of Energy, Office of Science, under Contract No. DE-AC02-06CH11357.
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We tested an MPS trigger module developed earlier for a vertical kicker and demonstrated that kicker-induced losses preceded the MPS-induced loss (typically 40-60 turns [2]). This trigger module will be adopted for the abort system. Note that the majority of APS beam dumps are initiated by an MPS trip, but ~10% are initiated by a Personnel Safety Systems (PSS) trip. In the latter case, the main dipole is inhibited as well as the rf, and beam losses are observed starting before the MPS trigger [2]. The abort kicker system may not be effective in preventing a quench for PSS trips, as observed elsewhere [6].

In order to kick out the entire beam, the kicker pulse waveform must be sufficiently long. 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.

Design

The abort kicker magnet is converted from a storage ring injection kicker magnet [7] by adding a free-wheeling diode across the magnet coil. The power supply is the same as for the injection kickers. With the same magnetic and electrical parameters, the kicker current—hence the mag-netic field— has the same rise time as the injection kickers. After the current reaches its peak, the magnet voltage reverses polarity and turns on the free-wheeling diode. The current initially decreases fast due to the effort to overcome the stray inductance in the free-wheeling diode circuit and to fully turn on the diode. Then, the current decays slowly, producing a long-lasting magnetic field.

Figure 1 shows the measured field pulse waveforms for the abort kicker, where Bρ = 23.3 Tm. The integrated field B·dl was measured with a long coil, where B is the magnetic field and l is the coil length. For a voltage set point of 10 kV, the peak kick is 1.3 mrad, and for 8 kV, the peak kick is 1.0 mrad. The waveforms are shown as a function of bunch index number, using a bunch spacing of 153 ns in the 24-bunch mode.

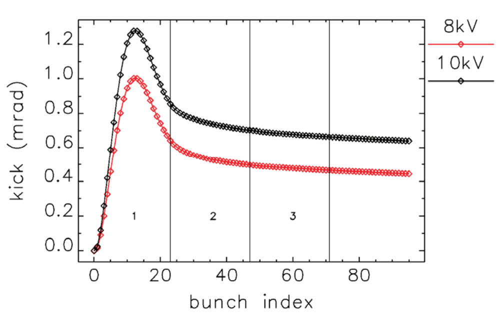

Figure 1: Abort kicker waveform kick angles calculated from measured integrated field B·dl divided by Bρ. The first three turns are marked.

SIMULATIONS

Multiparticle tracking was carried out using `elegant` [8], assuming 24-bunch mode. The standard model lattice was used, which gives tunes of (36.2, 19.3), chromaticities of (4.0, 6.4), effective x-emittance of 3.2 nm, and rms bunch length of 33.5 ps. These are close to the usual operating parameters without bunch-by-bunch feedback. Each bunch was modelled using 2k 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 loss distributions were analyzed for the measured abort kicker waveforms (Fig. 1), and the results are shown in Table 2. The beam is completely lost in 2 turns for a 1.3-mrad peak kick and 3 turns for a 1.0-mrad peak kick. The majority of the beam is lost on the thick septum chamber, as designed. No beam was lost in ID1 (SCU1) or ID6 (SCU0). Selected bunches were tracked using 200k macroparticles and 9σ cutoff, and it was confirmed that the loss distributions were the same.

Table 2: Simulated Beam Loss Results Using the Abort Kicker Waveforms (102 mA)

Peak kick (mrad)	Turn 1 (mA)	Turn 2 (mA)	Turn 3 (mA)	% lost at septum	% lost at ID1, ID6
1.3	72.4	29.6	0	97%	0%
1.0	50.1	31.7	20.2	96%	0%

Tracking shows that 3-4% of the beam is lost outside of the septum chamber. For a narrow range of kick values, between 0.74 and 0.83 mrad, particles miss the septum and are lost on small-gap ID chambers ID18 and ID19. The lost particles have both large horizontal and vertical trajectories (the latter due to coupling). Figure 2 shows the loss coordinates at ID19 on the first turn using the 8-kV waveform, and includes particles from bunches 8, 18, 19, 20 (total 3.8 mA). ID losses cannot be eliminated entirely, but can be minimized by tuning the kick amplitude.

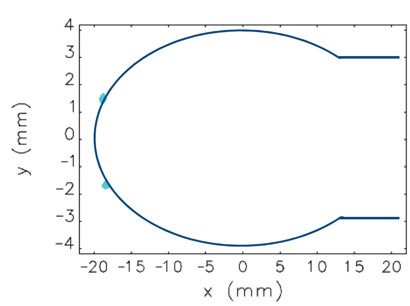

Figure 2: Simulated beam losses (cyan) on ID19 chamber shown with schematic of chamber profile.

Model Validation

The kick model was validated using the injection kickers and the turn-by-turn BPM beam histories [9]. Figure 3 compares the measured and simulated x,y

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trajectories for the first turn after kicking a single bunch with IK1 at 3 kV set point. The beam was not lost. Good agreement was found in the horizontal plane using a 0.33-mrad (0.11 mrad/kV) kick in `elegant`. In the vertical plane, the agreement is also good in the first turn, but the deviations are more significant in the second turn (not shown). The calibrated model is measured at the beginning of every run and may change with tuning during the run. This effect is under study.

The next investigation was kicking a single bunch with IK1 at 7.5 kV. In that case, the beam was lost. Figure 4 compares the measured and simulated x trajectories using the kicker calibration above. The trajectories < 10 mm are in agreement, but the trajectory maxima are not matched because the BPM response is nonlinear. The bottom panel shows the BPM sum signal, which shows losses mainly at ID10-11 and ID29-31. Tracking predicted losses mainly at ID21, with some losses at ID11. The discrepancy can be explained by uncertainty in the y trajectory; large y at large x trajectories leads to ID chamber losses. However, `elegant` does predict the ID loss locations modulo 10 sectors, due to the 4-fold symmetry of the horizontal trajectory. Large inboard x amplitude at ID1 (Fig. 4) raises the potential for losses; this demonstrates why IK1 is not ideal as an abort kicker. In the IK1+IK4 configuration in Table 1, simulations gave up to half the beam lost in ID1.

MARS [10] was used to track a single-bunch `elegant` loss distribution on the septum chamber, and preliminary analysis shows that the energy deposition is acceptable. We plan to import the secondary shower particles back into `elegant` to determine where they are lost. Another effect we plan to model is how the abort system performs with an initial orbit distortion. This would more realistically simulate initial conditions during a fault that causes the beam position limit detector system to trigger MPS.

CONCLUSION

An abort kicker system was studied using multiparticle tracking in `elegant`, simulating the loss distribution in 24-bunch mode. Tracking confirms the beam abort concept of a horizontal kicker in Sector 36, using the calibrated model. No beam is lost in ID1 (SCU1), ID4, or ID6 (SCU0). Occasional losses in ID18 and ID19 appear unavoidable but can be minimized. With the measured abort kicker waveform, the main simulated beam loss location is the thick septum vacuum chamber for a ~1 mrad peak kick. The entire beam is lost in ≤ 3 turns. Machine studies confirmed that strongly reducing ID6 beam losses using kickers can mitigate a SCU0 quench. The MPS trigger was tested with a vertical kicker. The abort kicker is scheduled for installation in 2015, when it will be tested for SCU quench mitigation. The effect of abort dumps on the septum chamber will be analyzed with MARS and `elegant` simulations prior to commissioning for operations. What is learned will be applied to an abort system for the APS Upgrade, where several SCUs are planned.

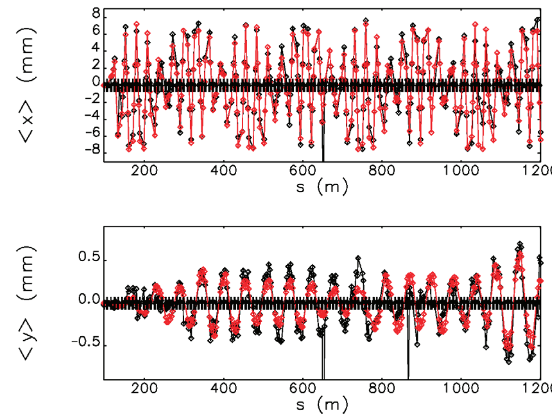

Figure 3: IK1 3-kV calibration: BPM data (black) compared with `elegant` 0.33 mrad kick (red).

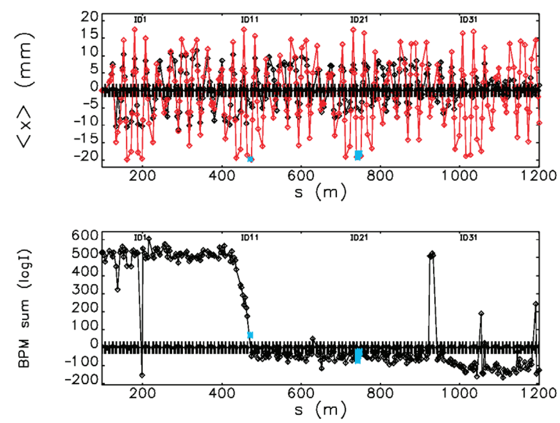

Figure 4: Trajectory (top) and loss distribution (sum, bottom) with IK1 at 7.5 kV, compared with `elegant` 0.8 mrad (red) and simulated loss distribution (cyan).

ACKNOWLEDGMENTS

Thanks to M. Borland, G. Decker, L. Emery, D. Horan, N. Sereno, A. Xiao, and A. Zholents for discussions and suggestions, and to A. Hillman for providing IK waveforms.

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