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SWAP-OUT SAFETY TRACKING FOR THE ADVANCED PHOTON SOURCE UPGRADE *

M. Borland, J. Downey, M. Jaski, ANL, Argonne, IL 60439, USA

Abstract

The Advanced Photon Source upgrade will operate in swap-out mode, which is similar to top-up but involves complete replacement of individual depleted bunches in a single shot. As with top-up, safety is a concern as this process will take place with beamline shutters open. We describe the methods used to model swap-out safety, including creation and validation of a full ring lattice based on 3D field maps. We describe a method of implementing complex, intersecting channels for electron beams and photon beams, as well as a method of easily identifying potentially dangerous stray particles. Numerous potential errors (e.g., magnet shorts) were modeled, giving requirements on performance of proposed stored beam and magnet interlocks.

INTRODUCTION

Since the APS Upgrade [1] will perform swap-out [2,3], a safety concern exists: injection with photon shutters open presents the possibility of injected-beam electrons entering a photon beamline. Intuition strongly suggests that this cannot happen while there is stored beam, so that safety is virtually assured by an interlock [4] that prevents injection with shutters open when stored beam is absent. If this is untrue, then the stored-beam interlock would need to be supplemented with additional interlocks to ensure that beam cannot reach a dangerous location while stored beam is present.

Several approaches have been taken to simulations of such accidents [5–8]. For APS-U, we use forward tracking as it is more straightforward and more readily incorporates the fact that there are multiple dangerous endpoints for errant electrons. It also provides results for use with radiation transport codes to understand whether electrons create a radiation hazard by impacting, say, a crotch absorber.

SIMULATION OVERVIEW

The primary simulation strategy involves positing a series of errors in a particular magnet in a particular sector, then performing tracking to determine whether there is a possibility that beam entering the sector could find its way to a "dangerous" location, e.g., inside a photon beamline. For the same error, we also determine whether other electrons entering the sector could exit the sector, possibly aided by downstream compensating adjustments.

If we find a condition where we simultaneously see dangerous and transmitted electrons, then the possibility of an accident exists. In this case, we check for the existence of a stable closed orbit, allowing for the possibility of automatic correction. If this analysis confirms that stored beam is possible, then the stored beam interlock is not sufficient. In that case, steps must be taken to prevent the condition from occurring, e.g., a voltage interlock on the magnet.

TRACKING METHODS

Tracking uses an acceptance-filling beam (AFB) at the entrance to a nominal sector, conservatively defined by the 22-mm inside diameter BPM apertures at the ends of the straights, ignoring the insertion device chambers. Over 17×10^6 particles with uniform energy range of $\pm 7.5\%$ were included in the AFB. The energy window is based on a planned booster extraction interlock, which will enable extraction only when the booster dipole current is within $\pm 2\%$ of the nominal value. Coupled with possible rf frequency swings, horizontal corrector swings, and the rf bucket half-height, this translates into an limit of less than $\pm 7.5\%$.

Because large amplitudes are relevant, we use 3D field maps for tracking and extend these field maps over the photon beamlines. Fields are sampled with spacing of 1 mm in all dimensions, compared to typical full magnet apertures of 26 mm. Tracking through 3D field maps in `Pelegant` [9,10] is accomplished using the `BRAT` element for bending magnets and the `BMXYZ` element for others. One challenge is accurate modeling of non-linear field variation (e.g., sextupoles, fringes) without excessively small grid spacing and amplification of noise. This is addressed using local 4^{th}-order 2D polynomial fits on an extended grid surrounding each particle's (x, y) location.

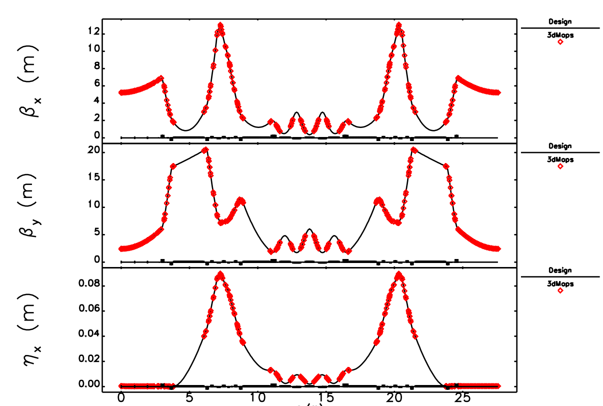

Figure 1: Comparison of 3D-field-map lattice to design.

The field maps do not correspond precisely to the design strengths. Using scale and position adjustments, we first matched the transfer matrix for each element, then the lattice functions, tunes, and chromaticities for a double sector. Agreement was excellent, as Fig. 1 shows. `Pelegant`'s

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ability to compute transfer matrices using parallel particle tracking [11], then optimize the matrices or derived quantities (e.g., tunes), made this computationally feasible.

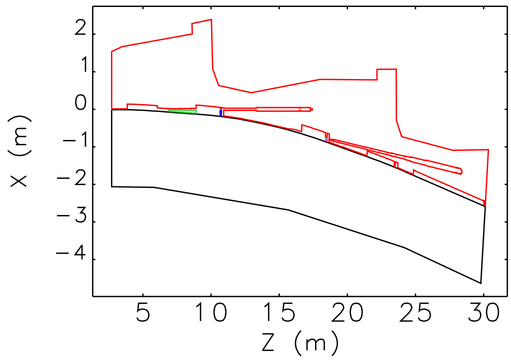

Figure 2: Mid-plane no-go contours for APS-U, showing vacuum and tunnel boundaries.

Because the vacuum chamber is multiply-connected, we use “no-go contours” — boundaries along metal or concrete surfaces—in the vertical midplane to define the apertures, see Fig. 2. These contours are derived directly from full-sector drawings and are conservatively extended to the full chamber height of ±11 mm. Determination of whether a particle is inside a boundary is quickly completed using winding number computations. After a run completes, lost particle coordinates are analyzed to find any in a “danger zone,” e.g., inside a photon chamber or on the edge of a relevant aperture. We sought, intuitively at this point, to identify particles that might cause showers that could reach potentially occupied areas. Future work will include delivering lost particle data to a radiation transport code to more fully assess potential problems.

ID BEAMLINES

For ID beamlines, the relevant magnets are the Q1 and Q2 quadrupoles, plus the M1 dipole. There are two M1 dipoles per sector, the first of which (A:M1) branches the electron and photon beams. Since the 80 M1 dipoles are on a string, a significant power supply error (above ~2%) is not consistent with stored beam. Hence, coil shorts seem the most likely cause of an accident at an ID beamline. To assess this, a comprehensive set of 15 single-short cases were modeled using OPERA [12]. Improbable multiple shorts were not simulated. However, owing to the coil geometry, it is possible to bypass 22 out of 23 windings with a single short, so this is something of a moot point.

Figure 3 shows that only for the most severe case are there dangerous particles identified together with transmission out of the just-downstream A:Q3 quadrupole. Although not included here, other studies have shown that the number of transmitted particles can be increased significantly using downstream steering elements. This is suggested already by the large number of particles that exit A:Q3.

Figure 4 shows the results for A:Q1 as a function of the fractional strength error (FSE), which suggest that these mag-

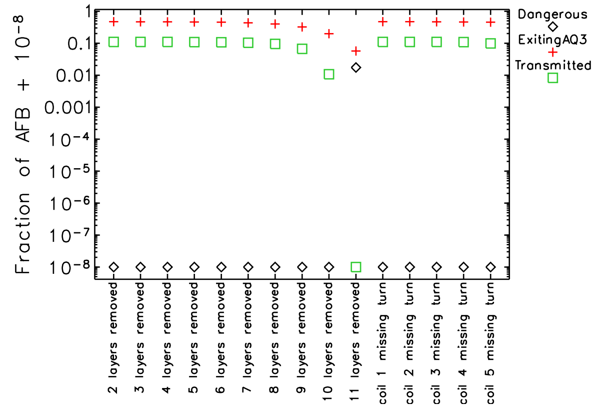

Figure 3: Assessment of safety for A:M1 dipoles.

nets will need to be interlocked. However, that conclusion needs to be verified by checking stored beam stability, since the required error is large, implying that large lattice correction effort is needed to restore stored beam. This might not be possible given limits on magnet strengths.

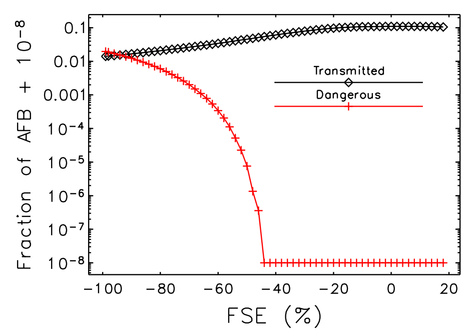

Figure 4: Assessment of safety for A:Q1 quadrupoles.

BM BEAMLINES

For bending magnet (BM) beamlines, we have so far looked only at power supply errors, which are much more probable than coil shorts. In particular, all transverse-gradient dipoles have a main quadrupole supply and a trim dipole supply. To study this, the main supply was varied by itself, with the trim supply at nominal or set for maximum outboard deflection. This was accomplished by scaling of field nominal maps and, in the latter case, addition of a uniform field inside the magnet.

These scans revealed potential problems with three magnet types near the BM branch point: A:M4, B:Q8, and B:M3. M3 and M4 are normal-direction bends, while B:Q8 is a reverse (i.e., outward) bend. Figures 5 through 7 show the results. The required errors are quite extreme, so once again we must verify the results with stored beam stability analysis. In addition, early indications are that adding insertion device apertures reduces the problem for the BM lines by reducing the phase-space volume of the AFB. Note that for all other magnets, no dangerous particles are generated, so the single-error analysis ends there.

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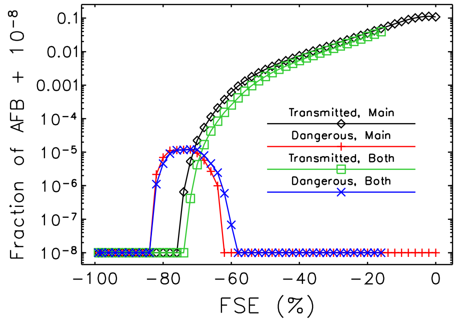

Figure 5: Assessment of safety for A:M4 dipoles.

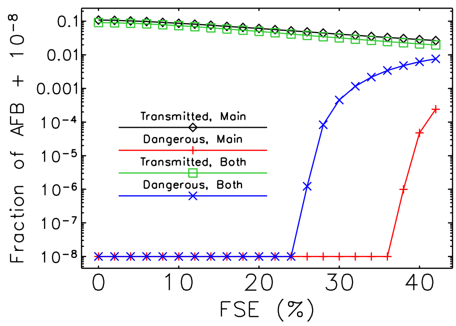

Figure 6: Assessment of safety for B:Q8 dipoles.

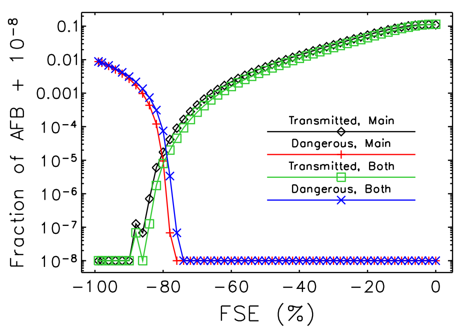

Figure 7: Assessment of safety for B:M3 dipoles.

STORED BEAM ANALYSIS

Having identified several possible accident conditions using a highly conservative method, we revisited the less conservative stored beam analysis, similar to [5]. Of particular interest is the time interval between loss of stored beam and potential generation of dangerous particles, since this determines whether an interlock can prevent delivery of a single electron pulse down a beamline. Using magnet inductances and resistances, we determined the decay constant τ for each magnet assuming a power supply (PS) trip. Values for individually-powered magnets range from 168 to 777 ms. We sampled each decay curve at 22.6 kHz, the update rate of the APS-U fast orbit feedback (FOFB) system [13], then used `elegant` to step through each point, performing a single step of orbit correction each time. Based on studies of the prototype FOFB [14–16], we corrected 20% of the orbit error on each step.

The simulations terminated when the closed orbit finder failed due to tune shifts associated with large orbits. As an indication of how conservative the tracking simulations are, for M4 and M3, the stored beam is lost at FSE values of -7.5% and -8.0%, respectively, which is about ten times smaller than the FSE that allows simple transmission to the end of the sector. The point at which this occurs implies, via the decay constant, loss of stored beam within a time $\Delta T_s = -\tau \ln(1 + \mathrm{FSE}_s)$ of the PS trip. Similarly, the appearance of possible dangerous particles occurs at time $\Delta T_d = -\tau \ln(1 + \mathrm{FSE}_d)$ using results like those shown in Figs. 5 and 7. If $\Delta T_{ds} = \Delta T_d - \Delta T_s <= 0$, then the stored beam interlock cannot prevent an accident, since the accident condition will exist before stored beam disappears. Otherwise, ΔT_{ds} is the time available for an interlock system to inhibit extraction of beam from the booster. For the M4 and M3 magnets, we find ΔT_{ds} = 193 ms and ΔT_{ds} = 693 ms, respectively. For the M1 magnets, which are on a single power supply, we find ΔT_{ds} = 30 ms; the value is short partly because these magnets have very low inductance. Still, 30 ms is a fairly long time for the interlock to react. These computations must be revised to include the cable resistance, which will reduce τ and thus the available response time.

CONCLUSIONS

Considerable progress has been made on swap-out safety analysis for the APS Upgrade. Initially, highly conservative simulations were performed that use tracking of an acceptance-filling beam (AFB) to determine the conditions under which particles might simultaneously transit a sector and impact a "dangerous" location. This suggests that near-total shorting of a coil in a single M1 longitudinal-gradient dipole could produce an accident condition for an ID beamline that would not be prevented by a stored beam interlock. Similarly, several transverse-gradient dipoles near the BM beamline branch point could produce such a condition. More recently, we added explicit analysis of the closed orbit in the presence of realistic fast-orbit feedback and found, not surprisingly, that the AFB tracking studies lead to extremely conservative conclusions. Coupled with the tracking results, closed orbit computations show that simple power supply trips cannot cause even a single-shot accident provided the stored beam interlock prevents injection within about 30 ms of loss of beam.

Future studies will include use of dynamic acceptance calculations to supplement closed orbit calculations, use of more realistic apertures in defining the AFB, and coupling to radiation transport calculations.

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