# TRACKING STUDIES OF TOP-UP SAFETY FOR THE ADVANCED PHOTON SOURCE*

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*Abstract*

The Advanced Photon Source (APS) is a 7-GeV, third-generation synchrotron radiation source. To provide more stable beam for users, we are pursuing a new operating mode called "top-up" [1, 2]. In this mode, the beam current is not allowed to decay as it normally would, but instead is maintained at a high level through frequent injection. A safety question with top-up mode is, during injection with photon shutters open can injected beam ever exit a photon beamline? This might happen, for example, due to full or partial shorting of a dipole coil. Extensive, detailed tracking studies were performed to assess the possibility of such an accident given the planned safety measures. We discuss the safety philosophy, the scenarios simulated, and the advanced computational techniques employed. A companion paper [1] discusses analytical estimates of top-up safety.

## 1 SAFETY ISSUES FOR TOP-UP

The basic safety issue for top-up is whether it is possible, through an equipment malfunction or other circumstance, to extract injected beam down a photon beamline. If this occurred, a significant radiation level would result outside the accelerator enclosure. For example, if a dipole immediately downstream of an ID straight section shorts (has zero field), the electron beam entering the dipole would continue on the same path as the ID photon beam and exit the accelerator enclosure. In principle, this could continue for an arbitrarily long time. In practice, radiation monitors would probably prevent this, but we considered this alone inadequate.

Instead, we started from the realization that synchrotron light sources are safe with photon shutters open when there is no injected beam, because stored beam cannot be extracted down a photon beamline as it will be lost on a aperture first. Extending this, we postulated that it is impossible to extract injected beam while maintaining stored beam, even when the two beams travel on different trajectories. If this is true, then top-up safety can be assured by disabling injection if stored beam is lost while shutters are open. Analytical methods [1] bolster one's confidence in this postulate, but provide no proof. As a result, we undertook tracking studies to further strengthen our confidence in this assumption.

## 2 SIMULATION METHODOLOGY

A "top-up accident" is a situation where stored beam exists while injected beam is exiting the accelerator enclosure via a photon beamline. This requires, at minimum, a fully or partially shorted dipole magnet that leads into a photon beamline (i.e., the dipole that shorts is the one that normally diverts the beam path from entering the photon beamline). At APS, 35 of 40 sectors each have the potential for two beamlines (see Figure 1), namely, an ID beamline on the upstream (AM) dipole and a bending magnet beamline on the downstream (BM) dipole.

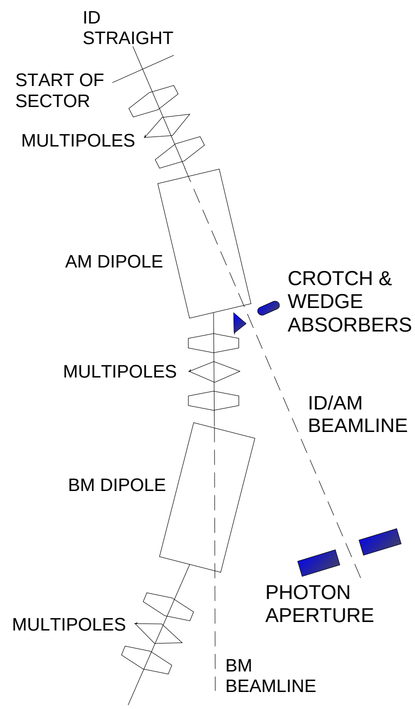


Figure 1: Schematic representation of an APS sector

For a fully shorted dipole, it is clear that injected beam can be extracted. For an unshorted dipole, it is clear that stored beam can survive. The possibility of an accident occurs somewhere between these two extremes, where one might have stored beam while extracting injected beam. (Note that the injected and stored beams need not enter the dipole at the same position or slope. If they did, it would be impossible to have an accident.) Hence, the simulations must be done with the degree of dipole shorting as a variable quantity, called the fractional strength error or FSE (equal to 0 for no short and -1 for a full short.) As illustrated in Figure 2, the simulations find the minimum FSE at which stored beam survives and the maximum FSE at which injected beam exits via the beamline. If the former is greater than the latter, we have a positive "FSE gap" and a safe situation.

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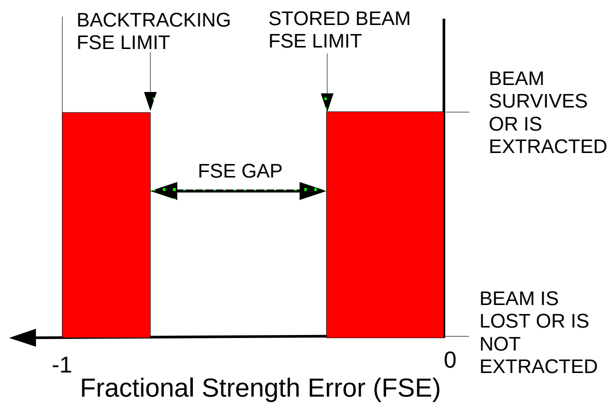


Figure 2: Illustration of the FSE "safety gap." In the middle region, stored beam is lost *and* injected beam does not exit the photon beamline.

In addition to dipole shorting, we simulate other faults that might conspire to produce an accident. For example, suppose that a magnet downstream of the shorted dipole also malfunctioned, producing a "conspiratorial" kick that compensated the missing field from the dipole. In such a scenario, the perturbation of the stored beam orbit could be greatly reduced, making the FSE gap smaller.

For each scenario we must simulate the stored beam and injected beam. For the stored beam we simply compute the closed orbit in the presence of a particular FSE and other errors; we then track a single particle on this closed orbit to see if it is lost on an aperture.

The acceptance of a photon beamline is easily computed from knowledge of the apertures and does not depend on magnet settings or other variables. Hence, for the injected beam, we chose to track backwards from the photon beamline using an acceptance-filling beam, ending at the upstream end of the ID straight. If any particles exit the sector, then we assume that they might also reach the injection point, i.e., the parameters of that simulation correspond to extraction of injected beam. If no backtracked particles exit the sector, then no injected particles could exit via the photon beamline under those conditions. Tracking only to the beginning of the sector greatly reduces the number of possible parameters that might influence the computations, with the downside that our results may be very conservative.

The apertures in the ring and photon beamline are clearly crucial to these simulations. In the simulations, we used all available apertures in the ring: the extrusion and (per sector) eight bellows, two "crotch absorbers," and three "end absorbers." Since the photon beamlines are drift spaces for the electron beam, we used only the two acceptance-defining apertures, namely, the crotch absorber and wedge absorber (which form a pair at the start of the beamline) plus the photon safety shutter. Not all sectors have identical aperture configurations, but all have the same elements.

Because the position of most of the apertures cannot be measured directly, we determined tolerances on their positions. In the simulations, these tolerances were included by increasing the apertures by the tolerance amount. For example, a $\pm 43$ mm aperture with a $\pm 5$ mm tolerance is simulated as a $\pm 48$ mm aperture. This extremely conservative procedure was necessary because of the time required to do randomized simulations using tolerances.

## 3 ACCIDENT SCENARIOS

We chose a number of scenarios that are most likely to lead to an accident. To make our results somewhat lattice-independent, we used 22 lattices with integer-spaced horizontal tunes from 18.2 to 39.2, except where noted. Also, except where noted, simulations vary FSE so that the limiting values (indicated in Figure 2) are found. The scenarios are the following:

*Type 1* A single dipole shorts, but no other faults occur.

*Type 2* A single dipole shorts and there is a worst-case compensating dipole field in a quadrupole or sextupole downstream of the dipole in the same sector. The worst-case compensating field is the one that best corrects the orbit distortion, limited by the maximum field that can be produced by the magnet. This scenario simulates both large single-multipole misalignments and shorting of the multipole (in a conservative way, as the quadrupole or sextupole field is not affected). Since the the compensating field is downstream of the dipole, it affects stored beam but not backtracked beam, which is the worst possible scenario.

*Type 3* A single dipole shorts and there is a combination of a gradient error and worst-case dipole field in a single quadrupole in the same sector. The gradient errors take 20 values that range between the limits that move the tune into the integer and half-integer resonances, subject to constraints on the polarity of the quadrupole. To reduce computation times, these simulations are performed only for $\nu_x = 35.2$ (the standard tune) and $\nu_x = 20.2$ (the worst case for Type 2). In addition, a fixed FSE is chosen for each of the stored-beam and backtracking runs. The result is evaluated and the FSE inputs are adjusted until approximate boundaries are found for each type of run. Once these are found for one aperture configuration, they are generally valid for similar configurations, which saves considerable computation at the expense of sometimes giving pessimistic estimates of the FSE gap.

*Type 4* A single dipole shorts and a single quadrupole in the same sector has its polarity reversed. These runs are done only for backtracked beam, as we assume that the tune error is compensated by adjustment of other quadrupoles in the ring, so that the stored-beam simulations from Type 1 can be used. This scenario is one that might arise if during replacement a power supply converter is miswired and the beam is stored again after adjusting the tunes using the other quadrupoles.

Figure 3 shows some representative data from simulations for Type 1. When all scenarios have been performed for an aperture configuration, we analyze the data to obtain the minimum FSE gap. Given the many conservative assumptions and the extreme nature of the scenarios, a positive minimum FSE gap indicates a safe configuration.

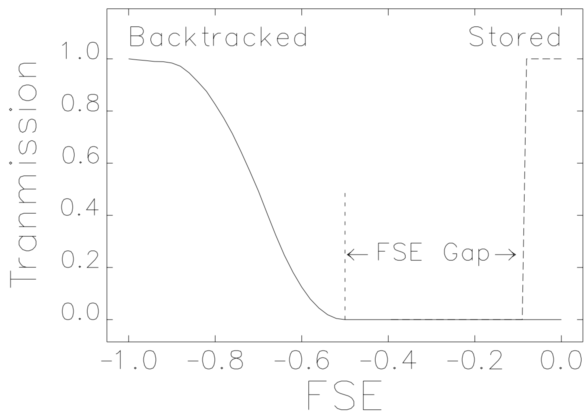


Figure 3: Typical Type-1 simulation results.

## 4 COMPUTATIONAL METHODS

Given the complexity of the top-up tracking, some might expect that we would have developed a new code for our problem. However, the program used was `elegant` [3], an existing code that does 6-dimensional tracking and other accelerator computations. The physics demands on the code were modest and could have been met by any number of codes. The only modification made to `elegant` was the addition of integration of field maps, necessary for backtracked beam simulations where the beam is very far off axis in sextupoles or quadrupoles. What was vital for our purposes was that `elegant` uses the Self-Describing Data Sets (SDDS) file format [4, 5]. Like all SDDS-compliant programs, `elegant` does essentially no postprocessing or data display itself. Rather, it relies on the powerful SDDS Toolkit, a group of about 70 generic data processing and display programs, that permits simplified development of postprocessing scripts for analysis of large amounts of data from many simulations.

For top-up safety tracking, about 500 runs are required for aperture configuration. These runs are grouped according to whether they simulate stored beam or backtracked beam, and according to the failure scenario. For each scenario type, a Tcl/Tk script is used to set up and submit the simulation runs. This script is itself usually invoked by another script that starts all the runs involved in a particular aperture configuration. These scripts greatly simplify the task of setting up and running a new round of simulations. A round of simulations for a sector takes about two days to run on 20 Sun Ultra 1 and Ultra 30 workstations managed by the Distributed Queueing System [6].

For each scenario, a specific script is used to postprocess the data and produce a simple results file (again, an SDDS file). These scripts also detect problems (e.g., missing data that might result from a workstation crashing), and to prevent using bad data, any simulations with problem data are deleted and must be run again. The user can easily do this by reinvoking the submission script. Like startup, postprocessing can be invoked with a single command. This command executes the scenario-specific scripts, then collates the scenario-specific results files into a single result file. In addition, the script produces a single value—the minimum FSE gap—showing whether the configuration is unsafe.

Both the startup and postprocessing scripts use the SDDS Toolkit for data preparation and analysis. In addition to using SDDS files for all output, `elegant` uses SDDS files for configuration of tracking and for tracking input. Most of these files are prepared automatically by the scripts or by other `elegant` runs (a few represent external input, e.g., the apertures, and are prepared manually). For example, in some scenarios a closed-orbit simulation with conspiratorial orbit correction will be performed, and a series of values giving quadrupole and corrector strengths will be saved. These data are loaded sequentially by a backtracked beam simulation, in order to replicate exactly the conditions of the stored-beam simulation. Thus, there is no manual copying of data from one simulation to another, speeding the work and eliminating the possibility of transcription errors (an important consideration given the safety-related nature of the computations). Other examples of SDDS data used as simulation input are the coordinates of the acceptance-filling particles for backtracking and the multipole strengths for the 22 different lattices used in the simulations.

## 5 ACKNOWLEDGEMENTS

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