ALS TOP-OFF SIMULATION STUDIES FOR RADIATION SAFETY*

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Abstract

We plan to commission top-off injection[1,2] at the Advanced Light Source (ALS[3]) in the near future. In order to guarantee radiation safety, we need to exclude the possibility of injecting electrons into the users' photon beam lines because of the very high radiation doses involved in case of such an event. This issue must carefully investigated and experimental tests cannot be easily performed. The only reliable way is through simulation. We have developed a scheme based in exhaustive simulations that accounts for all possible dangerous scenarios and that at the same time requires a reasonable amount of computing time. This paper describes such a method and presents a summary of the studies performed for the ALS at the present time.

MOTIVATION

The major difference between the present injection scheme at the ALS and the future top-off operational mode is that the beamline photon shutters remain open during injection. Such a difference introduces a major implication to radiation safety. In fact, a charge of 1 nC, that is the charge in a single injection pulse, if injected into a beamline, can create a radiation dose on the order of 100 rem which is completely unacceptable. Therefore we have to prove that no injected beam, regardless of reasonable magnet misalignment, power supply failures and/or mistuning, injector or injection magnet errors, etc, can ever propagate down a photon beam line far enough to expose people to dangerous dose rates. Because of the risk of high doses, even with a minimal amount of current per shot, a complete experimental proof is not possible, and the only way to investigate the issue is through tracking studies.

PARTICLE TRACKING

The aim of tracking is to check whether there is a case where the injected beam can accidentally go down a photon beam pipe creating a potentially dangerous radiation incident. The simulations required for the Top-off case can be quite different from other "ordinary" simulations performed for storage rings. For example, instead of circulating a few particles for many turns as in the typical dynamical aperture simulations, we use many particles but tracked for a short distance (fraction of the ring) and changing the lattice magnet settings within wide ranges. For example, a systematic scan of 10 parameters (magnet settings for example) independently varied in 10 steps includes already the impressive number of 10^{10} possible cases. Such a large number of cases can very soon make the simulation impractical. Therefore, an efficient simulation code must be developed for handling the large number of cases in an effective manner. At the same time, a careful analysis of the possible scenarios and risks is required in order to define simplifying assumptions and approximations that make the simulation study possible while still being rigorous.

Another major difference with respect to "standard" storage ring simulations is that for the Top-off case, the particle trajectories that could potentially lead to beam into the beamlines, are quite often very far away for the magnet centers. Maps or models for the magnet fields that include also the very nonlinear field profile for this large ransverse offset must be used. Additionally, the "standard" Hamiltonian used for ordinary tracking studies cannot handle such a special case and a proper Hamiltonian and integrator are necessary.

Finally, it is very important to take the proper credit of the vacuum chamber geometry, parts and components that ultimately define the aperture where the particles can go through. The proper representation of such components in the tracking code is fundamental and must be carefully verified by comparison with CAD drawings and measurements of the real position of the vacuum chamber components and magnets in the storage rings

SIMPLIFYING ASSUMPTIONS

Risk Analysis

Prior to any simulation study, we carried out a detailed risk analysis. The about 40 ALS beamlines were divided into four groups with members of the same group having similar characteristics, For each of this groups a "worst case" beamline has been defined by selecting the largest apertures among the ones in the same group. This allowed us to limit the tracking studies and analysis to the "worst-case" beamlines only.

In defining the tracking scenarios it is also fundamental to characterize the probability of simultaneous failure and/or missettings of ring components (magnets, power supplies, etc). The possible cases were classified by their probability of occurrence, and for example, two very low probability events, such as the simultaneous short in the coils of two of more magnets, was considered an event with extremely low combined probability and not considered. Eliminating the number of possible simultaneous events is the most effective way of reducing the simulation time.

* This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Material Sciences Division, U. S. Department of Energy, under Contract No. DE-AC03-76SF00098.

Inverse Tracking

We used the same simulation technique employed by APS for their topoff analysis [4], where the beam is tracked backwards from the photon beamline towards the injector. If no backward trajectory initiated from the phase space defined by the acceptance of the beamline is able to leave the sector where the beamline is, then the reverse is also true that no particle injected into the ring can go though the beamline. In what follows we will refer to this as inverse tracking.

Inverse tracking uses dangerous particles starting from the photon beam port. If the photon port is inherently safe, most of these particles are blocked in a short range by the vacuum chamber components as apertures, photon stoppers, etc.

The main advantage of inverse tracking with respect to the forward tracking is that in the simulations you have to go through a smaller number of magnets so that the computation time is significantly reduced.

One typically starts the simulations with a relatively small number of points in the beamline phase space. The particles are then tracked varying the magnets settings for all the possible combinations previously defined. This allows localizing those parts of the phase space that lead to dangerous trajectories (those that propagates during the back-tracking further down the sector towards the injection). Then one performs a second set of simulations with a much larger number of particles but now concentrated only in the dangerous phase space areas. Such a procedure allows for maintaining the simulation time requirements within acceptable values.

The ALS consists of 12 sectors. Each sector has a triple bend achromat structure [3]. Within each sector there are 5 possible light ports – one from the insertion device straight, one from the first bend, two from the second bend and one from the third bend. Preliminary analysis indicated that the port of most concern was the second port on the second magnet. This port is called the X.3 port. We have tested our procedure and made the complete analysis for one of the X.3 ports which had a large acceptance. The results can be seen if Fig. 1.

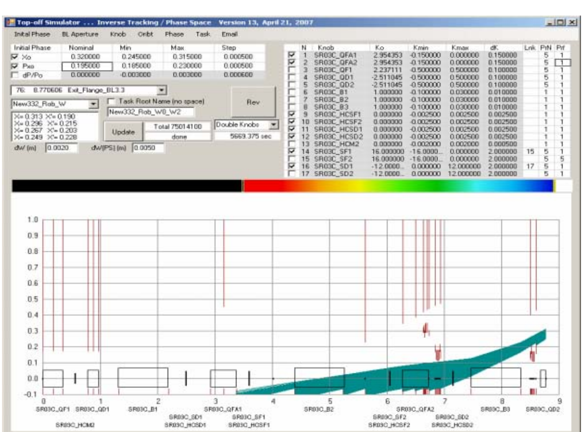

Figure 1. Inverse tracking results for one X.3 beamline

By applying our technique we were able to limit the longitudinal range of tracking only inside the arc section by excluding the magnets in the straight sections. This is important because quadrupoles and the steering magnets in the straight sections are part of feedforward and/or feedback systems, and including them would require adding a very large number of extra cases to be simulated. Therefore, this kind of localization was crucial for maintaining the simulation studies at a feasible level.

Tracking on the Mid-Plane

Another important assumption we did that allowed to significantly simplify the analysis, was to decouple the motion in the transverse planes and tracking the particles only in the horizontal one. When the field in magnets depended on the particle vertical position, we always assumed conservatively the highest value for the scanning range for the field in that magnet. This approach is conservative in that it did not allow us to take credit by limiting apertures in the vertical plane but on the other hand permitted to greatly simplify the geometry of beamline in the tracking code and to dramatically reduce the computation time.

SOLUTION

Magnetic Field Profiles

The magnetic field profile, obtained by numerical calculations for each magnet, was represented by a numerical table (1-dim, and/or 2-dim) over the range interest.

Independent Variable for Integration

We used a 2-dim (x-z) tracking code. There are two options for the independent variable of the integration; z, or time (t). We take z as independent to make the treatment of the magnet field profiles and the chamber geometries easier.

Hamiltonian

We use the following Hamiltonian in the x-z Cartesian coordinate.

$$H = \sqrt{(1+\delta)^2 - p_x^2} + V(x,z)$$

$$\frac{d}{dz}x = \frac{\partial H}{\partial p_x} = \frac{p_x}{\sqrt{(1+\delta)^2 - p_x^2}}$$

$$\frac{d}{dz}p_x = -\frac{\partial H}{\partial x} = F(x,z)$$

Here $\delta = \Delta P/P_0$=normalized energy deviation, and $F(x,z) = -\partial V/\partial x$. As we already have a tracking code (Bingo[5]) that uses this Hamiltonian including the vertical dimension, we took it and simplified for the use on the mid-plane. The bending magnet has been properly treated in the Cartesian coordinate by translating the particle coordinate at the entrance and the exit.

Integrators

There are two types of integrators available; the 2nd-order symplectic integrator and the 4th-order Runge-Kutta integrator. Both can be used with 1-dim and 2- dim field profiles.

The number of integration steps is determined to produce linear optics properly near the reference orbit without retuning the magnet strength. In case of ALS, we found that quad and bending magnets are properly integrated with 50 steps. When the 2-dim profile is used for the bend, we adjust it to 60 to be compatible with the longitudinal mesh size.

We were originally using the 2nd-order symplectic integrator with a 1-dim profile, and checked the validity of this method by using an independent code[6] for a few particular rays. Since we upgraded the code by adding the 4th-order Runge-Kutta and the 2-dim profile, we are able to compare the difference between the cases with 1-dim and 2-dim profiles.

Our experience tells that the 1-dim is basically sufficient but must be verified. Here the overhead of using the 2-dim profile at runtime is about extra 30% in time. Therefore, we will be using a 2-dim profile whenever we think it is better.

There is no visible difference in result that depends on the choice of the integrator as the longitudinal range is short. Therefore we can keep using the 2nd-order symplectic integrator.

Sextupole and steering magnets are modeled as thin elements with a 1-dim profile, which is also verified to be sufficient.

Chamber Geometry

The beam clearance aperture is determined by vacuum chamber walls, photon stops, photon exit ports and pipes. First, we worked on the CAD drawings and identified the apertures that are to be taken into the simulation code. Then, these apertures are replaced with lines in the x direction at several longitudinal locations. If a magnet is there at that longitudinal location, apertures are assigned to the nearest integration step with proper translation. If there is no magnet available, a marker is placed there. This is a process that is very time consuming and subject to make mistakes. Graphics display of the simulation program becomes important.

Parameter Scan

We have gone through a realistic risk analysis and established a list of scenarios that are to be simulated. A scenario is a set of parameters for scan, their scan ranges, and how multiple parameters are correlated.

A scan parameter is usually a magnet setting with a range to cover its various errors. Its magnet profile is scaled when setting is changed. The profile is also changed to model a magnet pole short. For example, we included a single pole short of quadrupole and sextuple magnets. These magnets are given multiple profiles and swapped at run time.

The risk analysis of the concurrency of the errors is important as these parameter scan must be nested. For example, assume two parameters to be scanned in 10 steps. If these events can happen simultaneously, they make 100 cases, otherwise we can scan them in series therefore they make only 20 cases. We must be careful not to assume high multiplicity. For this purpose, we grouped the risks into several categories based on their occurrences, and controlled the multiplicities by categories.

The definition of scan parameters and the way of using them varies depending on the scenario that can change at run time depending on the simulation result. Therefore the parameter assignment should be flexible.

The simulation code treats scan parameters in 2 steps; (1) the list of available scan parameters is defined in advance as a part of the input data file, and (2) we can select parameters from the list at run time, change their ranges and mutual relationships.

Inside the simulation code, the parameter scan loop with indefinite multiplicity is implemented effectively by using a kind of function pointers recursively.

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