TOP-OFF SAFETY ANALYSIS FOR NSLS-II*

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Abstract

Top-off injection will be adopted in NSLS-II. To ensure no injected beam can pass into experimental beamlines with open photon shutters during top-off injection, simulation studies for possible machine fault scenarios are required. We compare two available simulation methods, backward (H. Nishimura-LBL) and forward tracking (A. Terebilo-SLAC). We also discuss the tracking settings, fault scenarios, apertures and interlocks considered in our analysis.

TOP-OFF SAFETY

Like other modern synchrotron radiation light sources, NSLS-II will operate in top-off mode [1]. The top-off injection refers to injecting with photon beamline safety shutters open to maintain a near-constant stored beam current in the ring. In traditional non-top-off mode, photon shutters are closed during injection process to block any injected beam particles from escaping the storage ring enclosure and entering the experiment hall, where they would constitute a radiation hazard. Current plans call for injecting a charge of about 8nC once per minute for NSLS-II. Not even one pulse of injected electron beam can be allowed to escape through the shield wall, because the radiation dose would be unacceptably high. In order to allow top-off injection, it is necessary to carry out comprehensive tracking analysis to show that electrons cannot escape the ring enclosure even in the presence of magnet faults or injection errors.

METHODOLOGY OF TOP-OFF SAFETY ANALYSIS

At machine design stage, particle tracking simulations are used to guide us in specifying the location and size of beam collimators, magnet power supply interlock requirements, and other controls needed to avoid unsafe conditions. The simulations required for the top-off safety analysis are quite different from other particle tracking simulations performed for storage rings, which usually concentrate on the stability of long-term motion (dynamical aperture simulations). In top-off safety simulation, we need to track many particles within a specific phase space area for a short distance (fraction of the ring) and change the lattice magnet settings over wide ranges in order to include all possible machine fault scenarios, and consider particle trajectories far away from magnet center, and beyond good-field range.

We simplify the analysis and shorten computation time by constraining the tracking simulation to the magnet's mid-plane. Particles that have an offset in the vertical plane may experience a stronger vertical field in the vicinity of poles, which is simulated by variation of the magnet field. The variation range depends on magnetic field calculation result at the maximum allowed vertical offset limited by vacuum chamber transverse size.

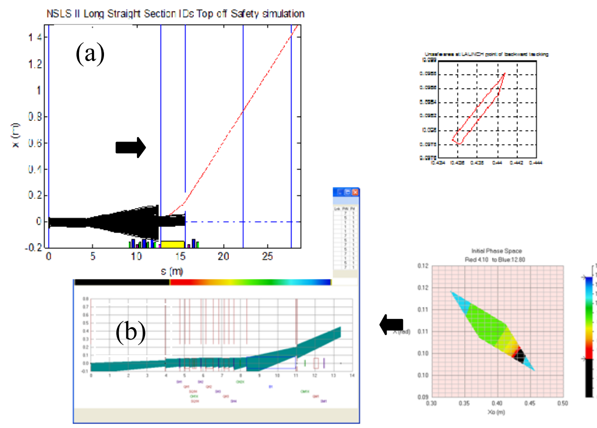

Figure 1: Forward (a) and backward (b) tracking.

There are two options available to do such simulation, backward tracking adopted by APS [2, 3] and ALS [4], and forward tracking by SPEAR 3 [5]. The forward tracking starts from an upstream source, and then tracks particles within a defined phase space area, which is determined by at least two physical apertures in magnet-free section, and checks if any particles can go through the physical apertures at beamline frontends (see Fig. 1 (a)). The backward tracking starts from a physical aperture within the shield wall at which it is safe to have electron scatter, and then tracks particles back into storage ring to check if there are any trajectories that can originate within the storage ring geometric acceptance (see Fig. 1 (b)). In principle these two methods are equivalent. We have checked this by using these two methods to analyze the same NSLS-II beamline and compared results. In the case of safe situation, forward tracking shows no trajectory originating from the ring acceptance can pass through safety shutter; and backward tracking shows no trajectory within frontend acceptance can track back into the ring acceptance. In the case of unsafe conditions, the phase space areas occupied by the unsafe particles given by the two methods overlap at the same longitudinal position.

We chose forward tracking in our simulation for two reasons. First, since our machine is still under design, we have an opportunity to specify some collimators to stop electron close to the ring. Forward tracking can help us detect the most effective position to install collimators. Second, most of our collimators in the ring and frontends are copper with a thickness of only several centimetres. In

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order to design the lead shield, we wish to know the location where the beam hits the vacuum chamber or collimators. Forward tracking can provide such information.

NSLS-II BEAMLINES

The NSLS-II has several types of beamlines. Each beamline has different physical apertures. We catalogue all beamlines into several classes according their source point location:

- Beamline with the source point in IDs at long straight section;
- Beamline with the source point in IDs at short straight section;
- Beamline with the source point in Three Pole Wigglers (TPW) and bending magnets.

The required apertures and controls to assure safety for each class of beamline is analyzed.

MACHINE FAULT SCENARIOES

In normal operation condition, e-beam and photon-beam are separated by bending electrons in dipoles, so that no e-beam can enter photon beamline frontends. In defining the tracking scenarios, we referred to other laboratories experience [4] and combined with our practical machine status. The goal of our work is to assure that we design the system such that no faults can lead to unsafe condition.

Magnets Faults

The possible magnet faults were classified by their probability of occurrence. Two very low probability events, such as simultaneous shorts in the coils of two of more magnets, was considered as an event with extremely low probability and not included in our simulation. So in each fault scenario, only one magnet can be completely or partially shorted. Partially short includes two cases: (1) whole magnet is partially shorted; (2) and just one of poles is completely shorted.

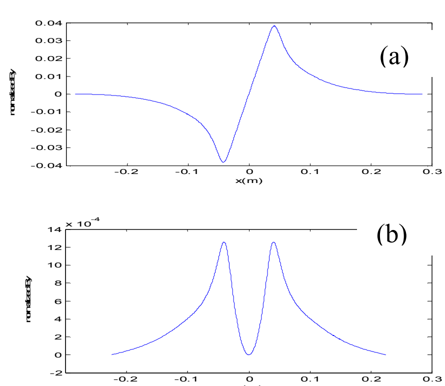

Figure 2: Quadrupoles (a) and sextupoles (b) vertical field component profiles on the mid-plane.

Since particle trajectories may be beyond magnet's good field range and some coils can be shorted, we can't use ordinary multipole models for simulation. All magnets' fields are scaled to their settings from the profiles obtained by numerical calculations for each magnet fault. Profiles for quadrupole, sextupole and corrector are represented by a 1-D numerical table (see Fig. 2). Dipole profile is a 2-D table so that it can include the fringe field.

Magnets Variation Range

In each scenario, one magnet fault is combined with all other magnets' possible variation. The variation range depends on the detailed magnet design and corresponding hardware configuration, such as power supply stability, adjustment range of trim coils, magnet monitoring and interlocks etc.

For example, in order to maintain the existence of the closed orbit, none of dipoles can be partially shorted-off by more than 5%, which can be fulfilled by specifying interlock requirement. At the same time, their trim coils can provide an extra maximum ±3% adjustable range. So dipoles can vary between -92~103%. By keeping another 2% for other unpredictable errors, the eventual variation range is 90%~105%. In fact, stronger dipole field is always good for safety, and then we only consider dipole strength below normal the setting value, that is 90%~100%.

As we mentioned in previous section, we constrain our simulation to mid-plane. In order to include the case of particles with vertical offset in quadrupoles and sextupoles, these two types of magnets vertical field can vary from 100% to 105%, which cover the maximum field in the vicinity of poles. The variation range of orbit correction magnets is chosen as their maximum allowed deflection angle ±0.8mard. Tab. 1 lists the magnet variation range and consideration criterion.

Table 1: Summary of Magnets Variation

Magnet Type	Variation Range	Consideration Criterion
Dipoles	90% ~ 100%	Power supply, trim coils, and closed orbit interlock
Quadrpoles	100% ~ 105%	Power supply, offset in vertical plane
Sextupoles	100% ~ 105%	Power supply, offset in vertical plane
Correctors	-100% ~ 100%	Maximum deflect angles

Aperture Misalignment

All physical apertures, like synchrotron radiation absorbers, can be deviated from design position because of many reasons, such as installation misalignment, form distortion due to synchrotron radiation heats etc, so we increase all apertures by the maximum allowed misalignment error, specified to be 2mm.

Energy Deviation of Injected Beam

Injected beam could have an energy deviation from its nominal value because of injector faults. Prevention of injected beam with certain amount of energy deviation to escape from safety shutter must be ensured. In the simulation, controls will be implemented to assure the maximum energy deviation is ±5%.

SAFETY ANALYSIS AND PARAMETERS SCAN

Here we use the long straight ID beamline as an example to describe how we implement analysis on its top-off safety. Two stick absorbers within the long straight section are chosen to determine the initial phase space area for tracking by four extreme rays (see Fig. 3).

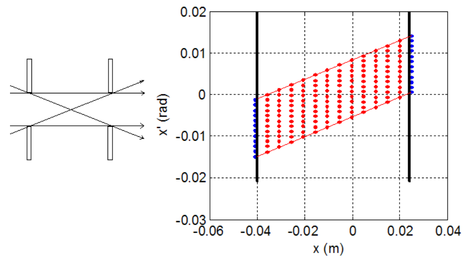

Figure 3 Determination of initial phase space area for forward tracking by four extreme rays.

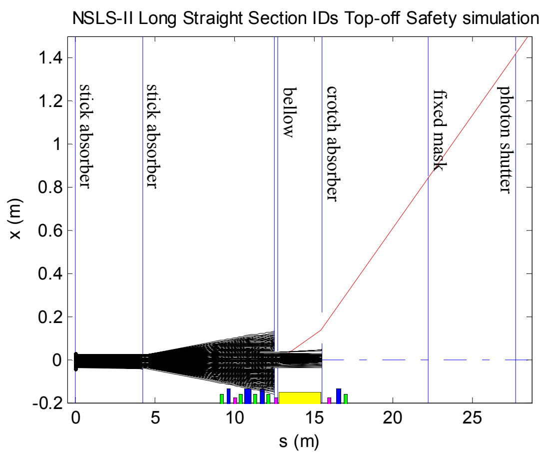

Figure 4: Beam trajectories (in black) in the normal condition. The central orbit of electron beam (blue dash line) is chosen as the reference, red solid line is the photon beamline centre, and blue solid lines are collimators.

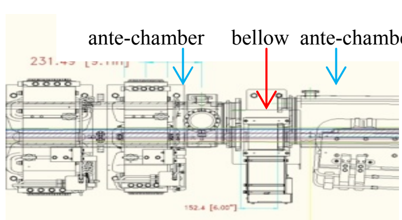

Figure 5: Two ante-chambers are separated by a billow.

We use element-by-element tracking method, the motion through each element is determined by integrating the differential equations of motion driven by the Lorentz force in the mid-plane. Particle's horizontal offsets are compared with the physical apertures to determine if they can pass through these apertures. The possible machine fault scenarios are simulated by varying magnet's setting. Fig. 4 shows beam trajectories in normal operation condition, and no beam can go through the crotch absorber. Some detailed study shows the bellow with ±38mm horizontal aperture between the multipole and the dipole ante-chambers can effectively collimate the particles with large horizontal offset at the upstream of dipole (see Fig. 4), its geometric design is shown in Fig. 5. As a result no beam can pass the crotch absorber.

In order to detect the possible dangerous scenarios as described in previous section, we need to scan the combination of the possible magnet faults, which is established by setting a list of varying parameters. The scan parameters include injected particles energy deviation, magnet faults types (completely short or partially short), magnet variation range.

Normally the number of scenarios is huge, but we can decrease it by constraining the magnet field variation range, which can be realized by specifying some monitoring and interlock requirements on magnet power supply.

For each scenario included in our scan, the magnet status and the final position where beam is stopped are recorded for further radiation safety analysis. If there are any scenarios which have trajectories travelling through the photon shutter in frontend, we must identify and specify controls to prevent them. Even when the electron beam is stopped by hitting the collimators, as we mentioned before, the 3GeV electron beam can create radiation shower, and we still need to design lead collimators to shield them. Therefore the location where beam is stopped is important information for the design of the lead shielding.

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