

APPLYING CASCADED PARAMETER SCAN TO STUDY TOP-OFF SAFETY IN NSLS-II STORAGE RING*

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Abstract

In this paper we introduce a new algorithm, the cascaded parameter scan method, to efficiently carry out the scan over magnet parameters in the safety analysis for storage ring top-off injection. In top-off safety analysis, one must track particles populating phase space through a beamline containing magnets and apertures and clearly demonstrate that for all possible magnet settings and errors, all particles are lost on scrapers within the properly shielded region. In the usual approach, the number of tracking runs increases exponentially with the number of magnet settings. In the cascaded parameter scan method, the number of tracking runs only increases linearly. This reduction of exponential to linear dependence on the number of set-points, greatly reduces the required computation time and allows one to more densely populate phase space and to increase the number of set-points scanned for each magnet. An example of applying this approach to analyze an NSLS-II beamline, the damping wiggler beamline, is also given.

INTRODUCTION

Many third-generation synchrotron light sources are running with top-off injection, which was first adopted by the Advanced Photon Source at Argonne National Laboratory [1]. In this operation mode, the stored beam current is maintained at quasi-constant level through frequent injection. In the National Synchrotron Light Source II (NSLS-II) [2], a 3GeV high-brightness synchrotron radiation source which is under construction at Brookhaven National Laboratory, we plan to provide a 500mA beam current with 1% intensity stability for users by employing top-off injection once per minute. An important safety issue is raised here: during injection with user beamline safety shutters open, injected beam must not be allowed to escape past all physical apertures and pass beyond the shield wall. One must assure that fault conditions, e.g. due to the shorts of dipole magnets, or mismatch of injected beam energy etc, cannot lead to an unsafe condition. To assure the safety in top-off injection mode, detailed simulation studies have been performed for existing and under-construction machines [3, 4]. In top-off safety analysis, a complete parameter scan must cover: (1) the possible permutations of magnet settings and faults; (2) the particles populating the area in phase space restricted by physical apertures; (3) the range of beam energy deviation due to the mismatch between injection system and storage ring. Based on the simulation results, both sufficient fixed apertures (passive protection)

and hardware interlocks (active protection) need to be specified to prevent injected beam from escaping through the open beamline safety shutters despite possible machine equipment faults. Therefore an efficient and conservative algorithm to scan parameters is needed for top-off safety simulation.

CASCADED PARAMETER SCAN

The usual approach to carry out top-off safety has been explained in the literatures [3, 6, 7]. Consider a beamline composed of k magnets (Figure 1) from its radiation source point to the frontend safety shutter, and for each magnet (i = 1, 2, ..., k) use n_i discrete set-points to cover its continuous full-range excitations and faults. The number of magnet fault permutations is $\prod_{i=1}^k n_i$. A straightforward method is to perform the parameter scan over the tree-shaped structure as shown in Figure 2. Typically there are about 10 to 12 magnets which must be taken into account in analyzing a NSLS-II insertion device beamline. If each magnet is chosen with 10 steps to represent its possible settings and errors, then the total number of permutations is 10¹⁰–10¹².

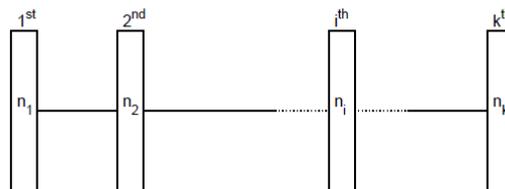


Fig. 1 Layout of a beamline with k magnets, each of which has n_i set-points

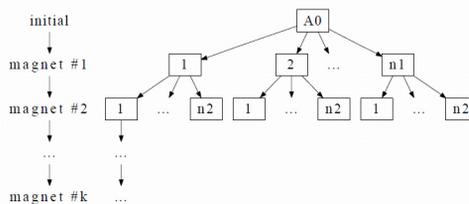


Fig. 2 Permutations in the usual parameter scan.

The basic idea of cascaded parameter scan [5] is combining the phase space areas occupied by the particles for each magnet setting (subsets) into a superset, then decreasing the number of particles by repopulating new particles within the superset. For a given initial area in phase space at the magnet entrance, the corresponding subsets for different excitations or errors at the magnet exit will usually have significant overlap, because we use discrete set-points to approximate a continuously variable

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magnetic field. Therefore in the overlapped region, the density of particles becomes very high after many overlaps. If the distance between some particles in phase space becomes very small, these over-dense points won't provide more useful information. Since we are studying a symplectic system, the area in phase space evolving under magnetic field is continuous and conserved.

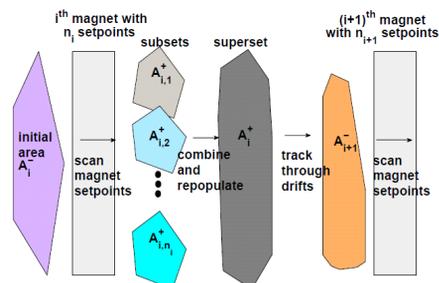


Fig. 3 Combination of subsets into a superset in the cascade parameter scan

The implementation of re-population is as follows: First, we combine all subsets at the magnet exit into a superset and define an area (usually it is a rectangle, see the largest rectangle in dash line in Figure 4) which can cover all the points in the superset. Then, we divide this area with a sufficiently small mesh grid. Next, all the particles in the superset are projected onto this mesh grid according to this rule: if there are any particles located within a grid (including on its borders), we will use the four points at the surrounding grid vertices to represent them. In the overlapping region of subsets, although the density inside a small rectangle can be very high, after re-population four particles at the grid corners will adequately represent them. The schematic process of the re-population technique is shown in Figure 4. After the re-population, the number of populated particles is proportional to the actual occupied area in phase space instead of the number of the magnet set-points. In this way, we reduce the dependence of the number of tracking runs on the number of magnet set-points from exponential to linear.

Special care must be taken when applying the re-population technique, because some unphysical particles have been introduced into the superset at its borders. For example, consider the original particle P_0 located within a grid and its four vertices P_1 , P_2 , P_3 and P_4 (see Figure 4). After re-population, the border of the original area is extended approximately by the order of the mesh grid dimension. Since we are studying a nonlinear dynamic system (the magnetic field profile is nonlinear, see Fig. 5), this area expansion could become quite large after passing through enough magnets. Thus unphysical particles can be introduced into subsequent tracking by employing a series of re-populations. This method is not good for a long-term tracking, because the area in phase space will expand exponentially even for small grid dimensions. But in the top-off safety simulation, we only need to track particles through a

small number of magnets. Once we choose the mesh grid fine enough, the area expansion in phase space is limited and controllable. In applying this method, we choose the suitable dimension of the mesh grid by decreasing it step-by-step until a convergent area is obtained after tracking through the whole beamline.

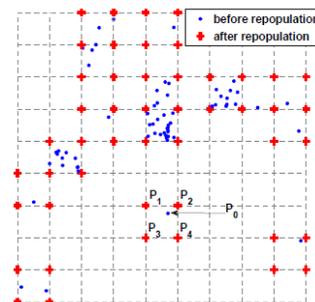


Fig. 4 Re-population particles in phase space

RETRACING UNSAFE TRAJECTORIES

If no particle can pass through all the given physical apertures along a beamline, the beam line is safe. But if some particles do pass through along the whole beamline in the cascaded parameter scan, this beamline is potentially unsafe. We need to figure out in which scenarios the beamline is unsafe and what these trajectories look like. So in this section, we explain how we can identify the corresponding unsafe range of magnet settings and determine the unsafe particle trajectories by retracing the unsafe particles back into the initial conditions. Interlocks can then be employed to assure that magnet excitations are kept in a range for which there is no unsafe particle.

The retracing process is implemented element by element in the opposite direction of cascaded parameter scan if any unsafe particles are found. For example, if we found unsafe particles at the exit of a given magnet, we trace them back to the entrance for each setting to identify in which settings the unsafe trajectories are possible, and where these particles coordinates are located at the magnet entrance. For this purpose, the particle's coordinates at each magnet entrance and exit are archived when we carry out cascaded parameter scan.

After retracing through the whole beamline, two important results can be obtained: First, we can determine the unsafe magnet setting ranges for which particles can pass through all the physical apertures. The unsafe magnet setting ranges can guide us to specify the necessary interlock requirements on magnet power supplies. Second, we can get the unsafe particle trajectories by connecting their coordinates between magnet entrances and exits. The trajectory information can be used to check the possibility to implement additional physical apertures to prevent them from passing through the beamline (see the application in NSLS-II beam line).

BACKWARD TRACKING

Backward tracking was first used for studying the top-off safety for APS ring [1], and then adopted by other facilities, like ALS [3]. The basic idea of backward tracking is to check if any virtual particles, originating from frontend acceptance, can travel through all the given physical apertures back into storage ring vacuum acceptance. The philosophy of backward tracking is that the trajectory of an electron going from one point to another point in a pure magnetic field is the same as the trajectory of a positron moving in the opposite direction. Thus if we can prove that no positron starting from the photon shutter in the frontend can enter the ring chamber acceptance with the existence of all physical apertures, we have proven that no electron starting from the ring acceptance can travel through the photon shutter under the same conditions. The beauty of backward tracking is the initial condition is easy to choose, and we can track virtual particles through limited number of magnets, instead of tracking injected particles from injection point for multi-turns.

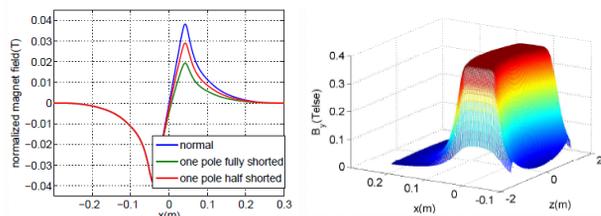


Fig. 5 Quadrupole (1d) and dipole (2d) profiles

Some important but conservative assumptions have been made in our simulations. (1) We perform tracking study only in the mid-plane. In principle, we need to track particle trajectories in a 4D $x-x_0-y-y_0$ phase space with different energy deviations, which would be very time-consuming. So in order to simplify calculation, we only simulate particle motions in the mid-plane, but extend the scan range of quadrupole and sextupole field by extra 7% to include particle's vertical offsets[3]. (2) Particles' initial coordinates (positions and angles) are limited by two physical apertures, the fixed mask and the photon shutter in the magnetic field free region. The maximum engineering tolerance $\pm 2\text{mm}$ has been included also. (3) To assure the unsafe particles can be detected by parameter scan, the diamond in phase space defined by two apertures is populated with very highly dense particles, because the area occupied by the potentially unsafe particles is quite small. (4) For each magnet, we use sufficient number of discrete set-points to represent their continuous tuning range and possible failure scenarios. We apply the same method to carry out the scan over injected beam energy deviations within $\pm 3\%$. (5) Particle trajectories are limited within the storage ring and beamline vacuum enclosure. (5) The field maps used in the simulation are calculated by the electromagnetic solver OPERA [8]. We use different field profiles for different magnet types (see Fig. 5) to save the

computation time without loss of accuracy in calculating particle trajectories.

APPLICATION ON NSLS-II BEAMLINES

As an example, we apply the cascaded parameter scan to study one of NSLS-II baseline beamlines, X-ray Powder Diffraction (XPD). XPD uses the radiation from a $2 \times 3.5\text{m}$ damping wiggler. The magnet and aperture layout of this beamline is shown as Fig. 6. We need to prevent the injected beam from escaping through the photon shutter during the top-off injection by deploying interlocks on magnet power supply and apertures.

We perform two runs. In the first run, we do backward cascaded parameter scan and find some unsafe trajectories. Then we retrace the unsafe particles to identify potentially unsafe magnet settings and their trajectories along the photon beamline pipe (red line in Fig. 6). So in the second run, we adopt sufficient interlocks on dipole field and add an extra aperture at the downstream of its crotch absorber (which is effective to eliminate the potential unsafe trajectories). Then we redo parameter scan to confirm that no unsafe scenario can exist any longer. For the second run, the retracing process is not needed, because no particles can survive through all apertures once interlocks and apertures are sufficient.

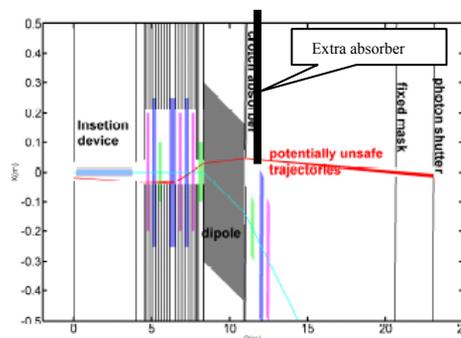


Fig. 6 XPD beamline layout and eliminate potential unsafe trajectories

REFERENCES

- [1] L. Emery and M. Borland, PAC'99, p. 2939, New York, 29 Mar 1999
- [2] <http://www.bnl.gov/nsls2/project/PDR/>
- [3] H. Nishimura et al., Nucl. Instrum. Methods Phys. Res., Sect. A 608, 2 (2009)
- [4] X. Huang et al., Nucl. Instrum. Methods Phys. Res., Sect. A 635, 1 (2011)
- [5] Y. Li, L. Yang, and S. Krinsky. Phys. Rev. ST-AB. 14, 033501 (2011)
- [6] Y. Li, et al., PAC'09, TU5RFP011, p. 1111, Vancouver, BC, Canada, 2009
- [7] A. Terebilo et al., Report No. SSRL-ACC- PHYS NOTE-007, 2009
- [8] OPERA-2d&3d Reference Manual, Vector Fields Inc., <http://www.vectorfields.com/opera.php>