FAILURE MODE ANALYSIS IN PREPARATION FOR TOP-UP INJECTION AT THE CANADIAN LIGHT SOURCE (CLS)

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Abstract

Top-up injection involves injecting beam with beamline safety shutters open. Consequently it is extremely important that no electrons enter the beamlines where they could be a potential safety hazard to beamline personnel. To investigate the likelihood that electrons could exit the storage ring various failure mode simulations have been done. The approach is to account for all possible injection trajectories and show that these particles will be intercepted by various storage ring apertures before they reach an amplitude that is deemed unsafe. This amplitude was chosen to be 50 mm and the field roll-off of all storage ring magnets were defined to this amplitude. Failure modes invested included injection kicker failures, uncorrected misalignment errors, off-energy injection and shorted storage ring magnet coils. Errors that would render it impossible to store beam were not investigated. As some particles reached amplitudes beyond the safe limit measures have been devised to eliminate these unsafe scenarios.

INTRODUCTION

To ensure that the storage ring is in a safe operating mode top-up injection will not be allowed to proceed unless beam is already stored in the storage ring. This ensures safe operation in several ways. First, to achieve stored beam the injection system and the storage ring must be set to operate at the same energy. Second, all magnets in both systems are most likely operating as designed. This is especially the case in the storage ring – all the main dipole magnets must be operating at correct polarity and thus act to deflect stray electrons away from the front ends of the beamline. If desired the storage ring tunes could be verified to indicate that the quadrupole magnets are also functioning correctly. At currents above 15 mA the orbit of the stored beam is not allowed to exceed 1.5 mm in either the horizontal or vertical plane. A stored current of 30 mA, therefore, will ensure that the storage ring is functioning correctly and the reference orbit is well corrected.

With 30 mA of beam circulating in the storage ring top-up injection will be allowed to take place if other safeguards are in place. It is possible that magnets in the booster-to-storage ring may fail at any time during injection. The following analysis demonstrates that even in the worst case injection into the storage ring will be safe and no electrons will be directed down any beamline.

Backward tracking from the beamline front ends can possibly demonstrate that the phase space for dangerous does not overlap with the phase space of any possible electron in the storage ring. In the CLS the field at the edge of the storage ring dipole magnets is unknown and backward tracking is undefined. For this reason, forward tracking is used to demonstrate that errant electrons cannot proceed down the beamlines.

TRACKING TOOL

It is assumed that the magnets in the booster-to-storage ring (BTS) transfer line can be in any state. Without getting into details of how this can happen, all possible trajectories that can get through the injection septum are considered – a so called shot gun injection. The particle co-ordinates are generated in the optics code as shown in figure 1. The co-ordinates are relative to the storage ring axis. The solid line around the blue dots represents the phase space acceptance of the of injection septum. To completely fill this phase space an array of particles slightly larger than the acceptance is generated as shown by the grey dots. Those particles that survive the collimating effect of the septum are used to investigate the injection loss scenarios in the storage ring. The accepted particles (green) are very close to emittance of the ideal injected beam.

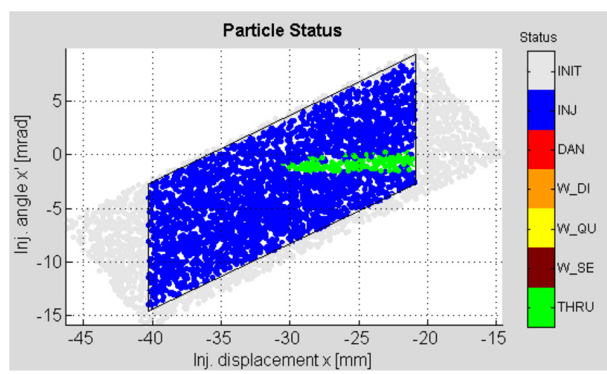

Figure 1: Shot gun injection into the storage ring with no errors. The injection septum geometry is shown by the solid line around blue particles. A uniform distribution of particles (grey) collimated by the septum provide a complete array of possible injected particles.

Tracking Loses in the Storage Ring

The storage ring is modeled with all physical apertures included as beam collimators. A MATLAB program is used to display the results of the particle tracking which is performed by DIMAD. Tracking is done over a few turns. The dipoles, quadrupoles and sextupoles have multipole components defining the fields to 50 mm. The magnet fields are derived from the theoretical field profiles that are in good agreement with the actual magnets. Results from tracking are displayed graphically in four different ways. Figure 1 is an example of the first display. Here, after several turns particles are accepted (green) or lost on some aperture. Blue indicates that no particle exceeded

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50 mm. If particles exceed 50 mm a warning will be indicated by other colours related to what kind of magnet this occurred in (dipole, quadrupole or sextupole). Since the tracking code is not defined for amplitudes over 50 mm these particles have unknown trajectories and are considered as possibly dangerous.

A second graphical display shows at what aperture particles are lost. An example is shown in figure 2. This plot is useful for correlating with the warnings described above. For example, injected particles lost during the first pass thru cells 1 and 2 are not considered dangerous. Details of the number of particles lost on each aperture and the turn number are also available. As several apertures share the same name this list can also be used to identify where particles are lost by checking the beam position.

(Knowing where particles are lost is also useful for choosing locations to do secondary particle shower studies. From these studies it becomes apparent that full energy particles are strongly forward peaked and absorbed in the aperture where they hit. Low energy particles can be produced at large angle but these a easily swept aside by the dipole magnets.)

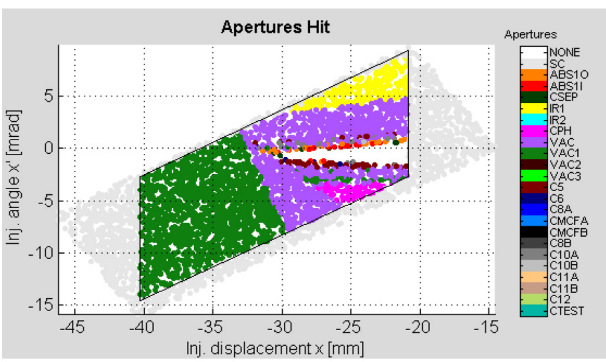

Figure 2: Apertures hit by shot gun injection.

Two other graphical displays are used to show the maximum amplitudes measured in the storage ring over the entire tracking process. Inboard (negative) amplitudes and outboard (positive) amplitudes are plotted separately. The outboard amplitudes are of special interest since it is these particles that may possibly exit the dipole magnets into a beamline front end. Amplitudes shown by a graded scale from 0 to 50 mm are considered safe. Particles that go beyond the 50 mm will displayed at black dots. These particles are considered dangerous and must be investigated further. Safeguards must be put in place to ensure that no particles are dangerous. For examples see figure 3 in the following sections.

ERROR ANALYSIS

As shown in figure 1for an error free storage ring lattice particles are either injected onto stable orbits or are lost before they reach amplitudes that are unsafe. Figure 2 gives a look at what apertures are hit by lost particles. **From this we can conclude that injection into the storage ring under normal operating conditions is safe for top up injection.** Here normal operating conditions means that the orbit in the storage ring has been corrected and the storage ring can be considered to be equivalent to the ideal machine.

As stated in the introduction a condition for top-up injection is to have beam storage ring. However, it is possible that during the injection process one or more of the injection kickers could fail to fire.

Less likely is the situation where the beam could be injected onto a wildly oscillating orbit. This is unlikely because the CLS orbit control system has a bad orbit threshold that will dump the beam is either the horizontal or vertical orbit exceeds 1.5 mm at any of the 48 beam position monitors. Even so, injection studies with large misalignments were done to cover that possibility that the bad orbit detection system fails.

Injection simulations were also done to study the effect of injecting beam that is off energy. This is another unlikely scenario in that the injection system would have to be energy matched to the storage ring in order to get beam into the ring in the first place. Parameters of the injection system would have to have been changed after the initial injection in order for an energy mismatch to occur.

It is possible to store beam with a single shorted coil in any one of the storage ring dipole magnets. Simulations for each possible dipole failure were done. Orbit correction for such situations requires kicks of greater than 1.0 mrad on either side of a shorted dipole. Such large kicks are not normally seen in the CLS orbit correction and it most likely that shorted coils would be obvious if they occurred.

Kicker Failures

The CLS injection system uses four kickers to move the storage ring reference orbit closer to the injection septum as particles are injected. Injection studies were done to simulate the effect of one or more kicker failures. With four kickers, then, there are 15 possible failure modes from single kicker failures to all failing. The four kickers, K, surround the injection point, IP, in the following configuration: (K1 K2 IP K3 K4). K1 is in cell 12, K2 and K3 are in the injection straight (cell 1) and K4 is in cell 2. For all 15 possible kicker failure modes not one mode produced orbits that exceeded 50 mm.

Misalignments

Injection into the storage ring with misalignments was studied for several randomly generated misalignment scenarios. Elements in the storage ring were misaligned such that horizontal orbit deviations up to 15 mm and vertical deviations up to 3 mm where generated. Amplitudes greater than these values would exceed the physical aperture of the machine and the beam would not be stored. 1000 particles were tracked for 5 turns through the misaligned lattice. In 25 different misalignments only one warning particle was found. Since one particle represents only a very small fraction of the normal

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injected beam (see green particles in figure 1) this is not considered a risk.

Off Energy Particles

Particles off energy by -6%, -4%, -2%, 2%, 4% and 6% were investigated. All energies except -2% produced unsafe (undefined) orbits. The most troublesome energy was -6% and the results for this are shown in figure 3. Here the maximum amplitudes are displayed. Black dots indicate amplitudes greater than 50 mm.

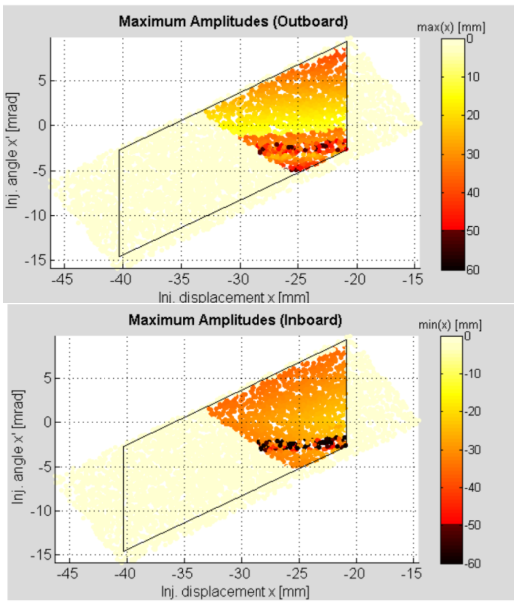

Figure 3: Top - Maximum inboard (negative) amplitudes for the case when energy is off by -6%. Bottom - Maximum outboard (positive) amplitudes.

Off energy particles present a possible unsafe injection condition. Such errant particles could be stopped by a single collimator at one of the sextupoles in cell 1. However, to avoid injecting off energy it should be possible to monitor the BTS and storage ring dipoles to ensure that they are operating at the same energy.

Shorted Dipole Coil

It is possible to store beam with a single shorted coil in a single storage ring dipole magnet. Since each dipole has 80 windings and a short between two windings would result in a 1.25% decrease in the magnetic field. (This does not account for saturation effects which would actually result in as slightly smaller change in the field.) With such a single shorted coil beam oscillations approaching the physical aperture of the storage ring would occur. Such oscillations can be corrected with the corrector magnets. Kicks of over 1 mrad would be required on either side of the dipole magnet that has a short. If more than one magnet has a short or if more than one coil is shorted in a single magnet it would not be possible to store beam.

Simulations of injection into the storage ring with a single shorted coil in a single dipole magnet were done for all dipoles. The simulations were done for the unlikely condition that the orbit was not corrected. For ten of the twenty-four dipoles dangerous orbits are observed.

It is unlikely that the storage ring would be operated with a shorted coil without the orbit being corrected. Injection would be difficult if not impossible. It is possible that the ring could be operated with the correction for the shorted coil in place. With this correction no large amplitudes are produce.

CONCLUSIONS

A summary of the injection simulations are shown in table 1 which shows the simulations for kicker errors, misalignments and off-energy injection. The "Status" column indicates injection is OK if no dangerous particles are found. For all the possible kicker errors all injections are OK. One set of misalignments, containing five different misalignments, has a "D" status. A close-up look reveals that less 0.03% of an ideal injected beam would reach warning amplitudes. It is interesting to note that with injection efficiency (Eff.) as low as zero any possible injected particle will be stopped by an aperture in the storage ring.

Off energy particles present the most problems with warnings for most scenarios. Injection and storage ring dipole power supplies will be compared to ensure energy mismatches do not occur. A shorted dipole coil poses some risk as well. Such shorts, however, will be obvious as large corrector magnet values will be required.

Even so, with proper safeguards in place we can conclude that top-up injection poses no safety hazard for the beamlines at the CLS.

Table 1: Summary of Tracking Simulations

#	File	Status	Description	Part.	Eff.	Turns
1	S1AAEm2	OK	Energy minus 2 per cent, not collimated	5000	4.4 %	4
2	S2AAEm4	D	Energy minus 4 per cent, not collimated	5000	0 %	4
3	S3AAEm6	D	Energy minus 6 per cent, not collimated	5000	0 %	4
4	S4AAEp2	D	Energy plus 2 per cent, not collimated	5000	0 %	4
5	S5AAEp4	DQS	Energy plus 4 per cent, not collimated	5000	0 %	4
6	S6AAEp6	DQ	Energy high 6 per cen, not collimated	5000	0 %	4
7	KAx123	OK	Kicker 1 is off	5000	1.1 %	4
8	KB1x34	OK	Kicker 2 is off	5000	1.6 %	4
9	KC12x4	OK	Kicker 3 is off	5000	1.4 %	4
10	KD123x	OK	Kicker 4 is off	5000	0 %	4
11	KExx34	OK	Kickers 1 and 2 are off	5000	0.5 %	4
12	KFx2x4	OK	Kickers 1 and 3 are off	5000	1.8 %	4
13	KGx23x	OK	Kickers 1 and 4 are off	5000	0 %	5
14	KH1xx4	OK	Kickers 2 and 3 are off	5000	0.5 %	4
15	KI1x3x	OK	Kickers 2 and 4 are off	5000	0 %	4
16	KJ12xx	OK	Kickers 3 and 4 are off	5000	0 %	4
17	KK1xxx	OK	Only kicker 1 is on	5000	0 %	4
18	KLx2xx	OK	Only kicker 2 is on.	5000	0 %	4
19	KMxx3x	OK	Only kicker 3 is on.	5000	0.1 %	4
20	KNxxx4	OK	Only kicker 4 is on.	5000	0.2 %	4
21	KOxxxx	OK	All kickers are off.	5000	0 %	4
22	MIS1	D	MISALIGNMENTS	5000	0 %	5
23	MIS2	OK	MISALIGNMENTS	5000	0.2 %	5
24	MIS3	OK	MISALIGNMENTS	5000	0.4 %	5
25	MIS4	OK	MISALIGNMENTS	5000	0 %	5
26	MIS5	OK	MISALIGNMENTS	5000	0 %	5

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