ANALYTICAL 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." 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 a full or partial short of a dipole coil. We discuss a number of analytical calculations that can be used to quickly assess top-up safety for a general ring. We also apply these results to the specific case of the APS. A companion paper in this conference discusses detailed tracking procedures for assessing safety.

1 INTRODUCTION

Injection into a storage ring is usually done with all photon safety shutters closed to protect against radiation accidents. As one can easily picture, injecting into a ring with shorted dipole will transport the injected beam down a photon beamline. If the safety shutter of the beamline is open, then the injected beam can exit the accelerator enclosure and potentially produce a large radiation dose.

A sufficient condition for safe injection with shutters open ("top-up" injection) is to ensure that no dipoles are shorted. This could be done directly by interlocking on the voltage across each dipole. An indirect way is to detect the absence of stored beam, which indicates the possibility of a shorted dipole. Since a shorted dipole will presumably preclude the storing of beam, one could inhibit injection with shutters open when no beam is stored in the ring. Injection could only proceed in an empty ring when the shutters are closed. This simple idea becomes more complicated when one includes the possibity of a partially shorted dipole.

It may not be obvious at first but the possibility of extracting beam into a photon beamline under normal circumstances is severely restricted by the internal apertures of the storage ring, in particular the dipole crotch absorbers. The extraction of injected beam can only occur from a short (full or partial) of a directly upstream dipole magnet. Accompanying magnet faults or lattice configuration errors may enhance the possibility of extraction, but they alone cannot extract the injected beam. A full proof of this statement as applied to the APS storage ring has been done using detailed tracking simulations and is given in an accompanying paper [1]. The stored beam detection safety interlock has been adopted for top-up operation at APS (for other details on top-up operation see [2]).

This paper will illustrate some of the principles of the tracking simulations. The discussion will refer to the field strength error (FSE) of a dipole as a variable quantity. A normal dipole has an FSE value of 0, while a completely shorted dipole has an FSE value of -1. These two limiting values of FSE correspond to two situations of definite character. We shall show that when $FSE = 0$ (i.e., the ring is normal), stored beam is possible but extraction of injected beam into a photon line is impossible. When $FSE = -1$, stored beam is impossible but extraction of injected beam into a photon beamline is possible.

For intermediate values of FSE, one has to estimate separately the possibility of stored beam or of the extraction of injected beam. If there are some values of FSE that allow both a stored beam and extraction of injected beam, then top-up injection is not safe. We shall show that in the case of APS and its apertures, there are no unsafe values of FSE.

At APS there are two X-ray beamline types of slightly different geometry: ID beamlines with photons exiting the first (AM) dipole photon port, and BM beamlines (bending magnet radiation) with photons collected from a point 1/8 th the distance downstream of the second (BM) dipole entrance. They will be treated separately where possible.

2 NORMALLY OPERATING DIPOLES

If all dipoles are operating normally, extraction of injected beam is impossible, no matter what other magnet faults or lattice configurations might be used. Illustration of this point involves tracking a hypothetical extracted injected beam backwards in the photon beamline.

To begin, assume that the photon beamline acceptance is very small, so that the backtracked beam is a single ray through the center of the acceptance-defining apertures. Using the simple geometry in Figure 1, the particle beam trajectory (going backwards) crosses the entrance of the dipole at the corner of the pole. In APS, the effective pole width is 112 mm and the vacuum chamber is 43 mm. Therefore, the hypothetical beam must have originated non-physically from the vacuum chamber, from which we conclude that extraction of beam is impossible. Note that since the backtracked beam is "lost" before leaving the dipole, no other magnet fault or configuration, including extreme injection kicker settings, can affect the result and produce an extracted beam.

The picture gets more complicated if one allows for the rather large acceptance of the photon beamlines. There is an increased chance for a particle to backtrack successfully
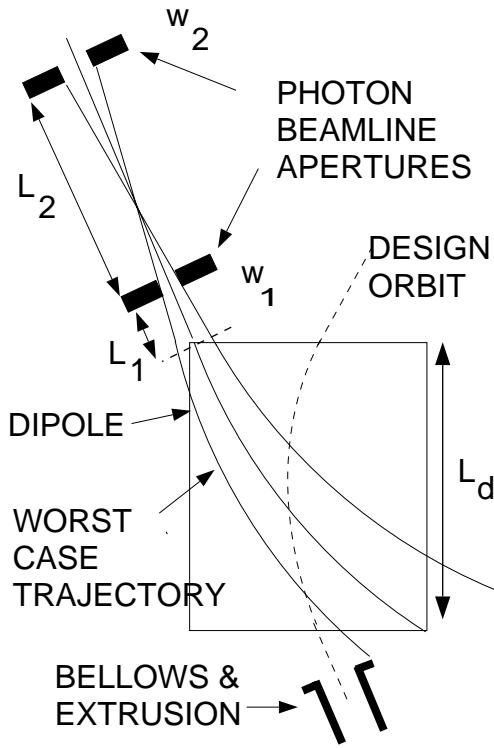
Figure 1: Schematic layout of dipole and hypothetical trajectories. Curvature is highly exaggerated for clarity.

through the dipole and disprove our case. The backwards trajectory that might best make it through the dipole is the one that starts out with negative coordinate (negative means inboard) at the last aperture and has a positive divergence angle (outboard direction) such that it just makes it through the first aperture. The dipole, of radius $\rho = 39$ m and length $L_d = 3.06$ m, is a distance L_1 (see Figure 1) from the first aperture. The apertures have widths w_1 and w_2, and are separated by distance L_2. The coordinate of the trajectory at the entrance of the dipole is $x_{\mathrm{traj}} = -w_2 + (L_d + L_1 + L_2)(w_2 + w_1)/L_2 - L_d^2/(2\rho)$. In both beamlines, whose aperture dimensions are shown in Table 1, the endpoint of the trajectory coordinate is beyond the -43 mm vacuum chamber limit.

Table 1: Photon aperture dimensions

| Beamline | L_1 | L_2 | w_1 | w_2 | x_{traj} |
	m	m	mm	mm	mm
ID	0.765	11.331	22	36	-78
BM	0.865	16.300	13	66	-88

3 SINGLE DIPOLE COMPLETELY SHORTING OUT

When a dipole is completely off, the injected beam can easily be extracted. The phase space of the injected beam with a typical betatron oscillation can easily fit inside the photon acceptance. When a dipole is off, a beam can-

not be stored. Though this may seem obvious, the extreme closed orbit created by such a perturbation on the dipole can be calculated from the standard formula $x(s) = \Delta x' \frac{\beta_x(s)\beta_{x,\mathrm{d}}}{2\cos(\pi\nu_x)} \cos\{|\phi(s) - \phi_\mathrm{d}| - \pi\nu_x\}$. $\Delta x'$ is the same as the dipole bend angle $\pi/40 = 79$ mrad. A small value for $\beta_{x,\mathrm{d}}$ of 2 m is a conservative choice, making the effect of the dipole perturbation small. Using a typical value of $\beta_x(s) = 20$ m for apertures around the ring and maximizing the cos term (since there are apertures at all phases), we obtain a closed orbit distortion of about 250 mm, compared to a horizontal aperture of 43 mm.

4 SINGLE DIPOLE PARTIALLY SHORTING OUT

From the above, we have explored only the two limiting values of field strength error for a dipole. We expect that stored beam will be possible for an FSE range of $\mathrm{FSE}_{\mathrm{stored}}$ to 0, and extraction of the injected beam will be possible for an FSE range of -1 to $\mathrm{FSE}_{\mathrm{extr}}$. It is important for top-up safety that the ranges do not overlap, i.e., $\mathrm{FSE}_{\mathrm{gap}} = \mathrm{FSE}_{\mathrm{stored}} - \mathrm{FSE}_{\mathrm{extr}} > 0$.

The FSE limit for a stored beam, $\mathrm{FSE}_{\mathrm{stored}}$, can be estimated from the formula for a closed orbit of a linear lattice due to a point orbit kick, as used above. One obtains an expression for the maximum orbit kick allowed for a uniform aperture x_{ap} around the ring $\delta x'_{\mathrm{lim}} = \frac{2x_{\mathrm{ap}}}{\sqrt{\beta_x\beta_{x,\mathrm{d}}}}$. Using the aperture of the vacuum chamber extrusion of 43 mm (the other smaller apertures around the ring are ignored for simplicity), then one gets a limiting kick angle of $\delta x' = 14$ mrad, which gives $\mathrm{FSE}_{\mathrm{stored}} = -0.17$.

The FSE limit for an injected beam is estimated approximately as follows. We consider only the trajectory centered on the photon beam axis and assume a parabolic negative trajectory through the whole length of the dipole. One equates the backtracked trajectory using the limiting FSE with the aperture of the dipole: $x_{\mathrm{ap}} = -(1 + \mathrm{FSE})\frac{L_d^2}{2\rho}$. For an aperture of 43 mm, we get $\mathrm{FSE}_{\mathrm{extr}} = -0.61$.

Comparing the two results above we see that $\mathrm{FSE}_{\mathrm{gap}} = \mathrm{FSE}_{\mathrm{stored}} - \mathrm{FSE}_{\mathrm{extr}} > 0.47$, and therefore the ranges of FSE for stored beam and extracted injected beam do not overlap. To the extent that the assumptions of these computations are correct, top-up injection is safe.

A better estimate of the FSE limit for an injected beam involves detailed tracking [1]. The full acceptance of the photon beamline and the unusual edge focusing due to the beam exiting the side of the dipole are included, both of which will weaken our case. However, particle tracking includes magnets and apertures upstream of the faulty dipole, which strengthen our case. These effects roughly cancel out, giving a value of $\mathrm{FSE}_{\mathrm{extr}} = -0.60$, which doesn't change the conclusion.

4.1 Effect of Orbit Correction

Steering magnets between the injection point and the shorted dipole will displace both the injected beam and the

stored beam within the same apertures, without changing the separation in phase space of the two beams. Though the FSE limits for the extracted injected beam and the stored beam may vary in an actual ring with arbitrary steering between the injection point and the shorted dipole, the quantity $\mathrm{FSE_{gap}} = \mathrm{FSE_{stored}} - \mathrm{FSE_{extr}}$ is not expected to change, and any conclusions obtained for an unsteered beam are unchanged.

However, a steering magnet placed downstream of a shorted dipole may partially compensate the error on the dipole while leaving the extracted injected beam unchanged, since the injected beam never sees the steering magnet. This possibility will change $\mathrm{FSE_{stored}}$ for the worse while leaving $\mathrm{FSE_{extr}}$ unchanged.

A possible source of steering is a regular horizontal corector magnet, with a maximum kick for a 7-GeV beam of 1.2 mrad, which is small compared to the $\mathrm{FSE_{stored}}$ angle equivalent of 14 mrad. The other possible sources of such steering are quadrupole and sextupole magnets shorted in such a way that a strong dipole field is produced. To be conservative, we use the peak field value the multipole can produce when operating at maximum current of the power supply. The maximum kick for a 6-GeV beam produced by the sextupoles and quadrupoles ranges from 24 to 71 mrad. This at first appears to be a serious problem since the dipole field error could apparently be compensated to maintain a stored beam while the injected beam gets extracted out of the dipole.

However, the betatron phase difference between the dipole and the multipoles works in our favor to impede the ability of these shorted multipole elements to reduce the orbit distortion. The length of the dipole itself serves to provide some phase advance separation that reduces the ability of outside kicks to correct the orbit distortion produced by the dipole. An approximate expression for the maximum possible relative increase in $\mathrm{FSE_{stored}}$ aided by a steering element can be derived as follows. We start with the closed orbit formula and simplify the expression by making $\beta_x(s)$ constant and introducing one oscillatory term for the shorted multipole dipole kick, $\delta x'_{\mathrm{M}}$. Dropping common factors, we get two oscillatory terms,

$$-\mathrm{FSE}(\pi/40)\cos\psi(s) + \delta x'_{\mathrm{M}}\cos\{\psi(s) - \Delta\phi\},$$

where $\psi(s) = \phi(s) - \phi_{\mathrm{d}} - \pi\nu_x$ and $\Delta\phi$ is the phase separation between the shorted dipole and the multipole steering element. The idea is to choose a value of $\delta x'_{\mathrm{M}}$ to minimize the effect of the FSE term. Solving graphically with phasors, the orbit oscillation for a given FSE can be reduced by a factor $\sin\Delta\phi$, and the corresponding correction angle is $\mathrm{FSE}(\pi/40)\cos\Delta\phi$. Thus for a given aperture, the FSE limit is increased in magnitude by factor $1/\sin\Delta\phi$ which is always greater than one.

Table 2 shows the estimated increased magnitude $\mathrm{FSE_{stored}}$ values, which range from the original -0.17 to -0.29. Since $\mathrm{FSE_{stored}} = -0.61$, then we are still safe for top-up injection. Different lattices may have different original $\mathrm{FSE_{stored}}$ and $\Delta\phi$'s, in which case the possible $\mathrm{FSE_{stored}}$ will have to be re-evaluated.

Table 2: Estimated increase of $\mathrm{FSE_{stored}}$

Dipole	Location	$\Delta\phi/2\pi$	$\mathrm{FSE_{stored}}$	$\Delta x'$ mrad
AM	end of dipole	0.16	-0.20	7
AM	A:S3	0.18	-0.19	6
AM	A:Q4	0.23	-0.17	2
AM	A:Q5	0.25	-0.17	0
BM	end of dipole	0.10	-0.29	11
BM	B:S2	0.11	-0.27	10
BM	B:Q3	0.13	-0.23	9
BM	B:Q2	0.14	-0.22	9

5 INJECTION ENERGY ERROR

A higher energy beam injected into the SR will be deflected less by the dipoles, making it easier to extract down a photon beamline. A positive relative energy error, $\Delta p/p$, in an injected beam will change the $\mathrm{FSE_{extr}}$ to $(1 + \mathrm{FSE_{extr}}) * (1 + \Delta p/p) - 1$.

The maximum energy output of the booster is 7.7 GeV. In addition, we installed an interlock for the storage ring main dipole current circuit that prevents top-up operation below 6 GeV. Therefore, the largest possible energy error is about 28%. Apertures also limit the energy error. There are one and a half sectors between the injection beamline and the first photon beamline, which ensures that an off-energy beam will experience a dispersion trajectory through apertures. The dispersion in the standard lattice is 188 mm at the 31-mm crotch absorber aperture, giving a realistic limit to the energy error of 16%.

The maximum $\Delta p/p$ of 16% reduces the magnitude of $\mathrm{FSE_{extr}}$ from -0.60 to -0.536, but does not change the conclusion that top-up is safe. Using the 28% value for $\Delta p/p$ results in $\mathrm{FSE_{extr}} = -0.488$, which again does not change the conclusion.

6 ACKNOWLEDGEMENT

7 REFERENCES

[1] M. Borland, L. Emery, "Tracking Studies of Top-Up Safety at the Advanced Photon Source," these proceedings.

[2] L. Emery, M. Borland, "Top-Up Operation Experience at the Advanced Photon Source," these proceedings.