OPTIMIZED SEXTUPOLE CONFIGURATIONS FOR SEXTUPOLE MAGNET FAILURE IN TOP-UP OPERATION AT THE APS*

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Abstract

Recently there was a situation at the APS when one sextupole power supply failed during top-up operation (all magnets at the APS have separate power supplies). The beam was not lost, but the lifetime decreased significantly to the point where it was hard for the injectors to provide enough charge for top-up injections. Luckily, the power supply was able to reset quickly, and the operation was not compromised. One can anticipate similar failures in the future when it would not be possible to reset the power supply. In such a case, the APS would need to operate with lower lifetime until the next intervention period. Here we present an optimization of the sextupole distribution in the vicinity of the failed sextupole that allows us to partially recover the lifetime. A genetic optimization algorithm that involves simultaneous optimization of the dynamic and energy apertures was used [1]. Experimental tests are also presented.

INTRODUCTION

Recently during top-up operation we had a situation when the power supply for sextupole S15B:S3 failed. The beam was not lost, but the lifetime dropped from 490 to 330 minutes. Operators had to increase the injected charge to keep up with the lifetime-related beam losses. After some time, the sextupole power supply was reset and the lifetime returned to the usual level. We can anticipate similar failures in the future, and in some cases the power supply might not be able to reset. In such a case, the storage ring would need to operate until the next intervention period with lower lifetime. To partially mitigate the effect of the failed sextupole, we decided to attempt to improve the lifetime by varying strengths of sextupoles around the failed one.

It is well known that breaking sextupole symmetry leads to decreased dynamic and momentum aperture. That is what we saw in the example above. We have recently found [1] that optimization of individual sextupoles can improve the performance of a lattice with broken symmetry. That work was based on idea that when the lattice functions lose local symmetry, the sextupoles near that location can be readjusted to partially recover the lost symmetry. We used this approach to design a lattice for the APS upgrade that includes several symmetry-breaking customized sectors and still has dynamic aperture and lifetime almost as good as the APS symmetric lattice. Here we will use this approach in an attempt to recover the symmetry lost when a sextupole power supply turns off.

OPTIMIZATION TECHNIQUE

We used the optimization technique developed in [1] with slight modifications. In this method, we use many computers simultaneously to evaluate the penalty functions for different sets of varying parameters. After completion of a sufficient number of evaluations, a genetic algorithm is used to breed new candidate configurations based on the best configurations seen so far. The process continues until a sufficiently good solution is obtained or until the results stop improving.

In our previous work, we used multi-objective optimization with two penalty functions derived from the area of the dynamic acceptance and calculated lifetime. We use term "dynamic acceptance" here as opposed to "dynamic aperture" to emphasize that the stability area calculation is performed in the presence of all physical apertures in the ring. The dynamic acceptance is what determines the injection efficiency. Instead of using the dynamic acceptance for optimization, in this application we decided to directly optimize the injection efficiency.

Injection efficiency is simulated by tracking a bunch of particles, with parameters of the beam from the APS booster, for several hundreds of turns. The fraction of survived particles gives the injection efficiency. Since the injection efficiency has a limit of 100% that cannot be exceeded, it might not be an ideal penalty function for a multi-objective optimization. To make it harder to achieve the maximum injection efficiency, we increased the initial amplitude of the injected beam by 10%.

The Touschek lifetime is computed from the local momentum aperture (LMA), the Twiss parameters, the beam emittances, and the bunch charge using the program `touschekLifetime` [2], which is based on Piwinskis formalism. LMA is calculated by tracking a particle with increasing momentum deviation starting from different locations along the lattice.

Our optimization technique relies solely on tracking. Although any tracking code can be used, the ability to create fully scripted simulations is essential, since lattice adjustments and tracking must run without human intervention. We use the tracking program `elegant` [3], the SDDS Toolkit [4], and geneticOptimizer [5].

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SEXTUPOLE OPTIMIZATION

APS has seven sextupoles per sector placed symmetrically around the center of the sector (one sextupole is exactly at the point of symmetry). This divides sextupoles into four families. It seems that we would need to run optimization for four sextupole locations, but we decided to do it for all seven locations to see if the optimization would find different sextupole solutions.

As was mentioned in [1], it is important to run optimization for the lattice with errors. Errors are required to excite resonances that otherwise would be canceled in an ideal machine. Also, without errors we would not have coupling. Instead of using random error set, we used a calibrated SR model. The calibrated model is derived using response matrix fit and is the best representation of the real storage ring that we can get. It has both quadrupole and skew quadrupole errors.

Since the symmetry disturbance is local, the correction should probably be local too. In our previous work [6] where we adjusted sextupoles to improve local acceptance at the location of the small aperture, we found that 14 sextupoles on each side of the aperture were required to significantly affect the local phase space. However, here we decided to use three sextupoles on each side of the failed one to reduce the number of variables and optimization time. It was also a convenient choice because APS has seven sextupoles per sector so we would be varying one sector worth of sextupoles (counting the failed sextupole).

We used optimization based on a multi-objective genetic algorithm. On each evaluation, `elegant` is used to adjust the chromaticity back to the designed values after the sextupole changes, then it calculates injection efficiency and LMA. Using those results, the lifetime is then calculated. Figure 1 shows examples of two optimizations where all evaluation results are shown in lifetime-injection efficiency space.

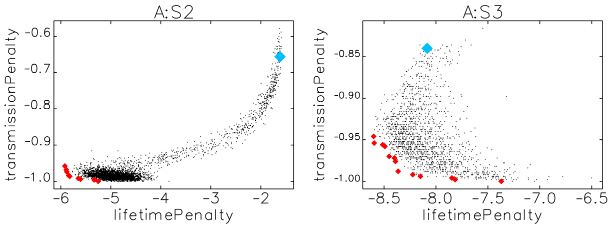

Figure 1: Evolution of the lifetime and injection efficiency during the optimization for A:S2 (left) and A:S3 (right). Blue point: starting point. Red points: highest ranked solutions. Black points: other solutions.

Figure 2 shows the LMA calculated by `elegant` for the first six sectors. The black line gives the momentum aperture for the initial model when all sextupoles are symmetric. After the A:S2 sextupole is turned off, the momentum aperture is decreased as shown by the red line, which leads to lifetime reduction. After the sextupole correction is applied, the momentum aperture is partially recovered (blue line). Figure 3 shows dynamic aperture for the same three cases. Sextupole correction allows increasing the dynamic acceptance after the sextupole failure, which will improve the injection efficiency.

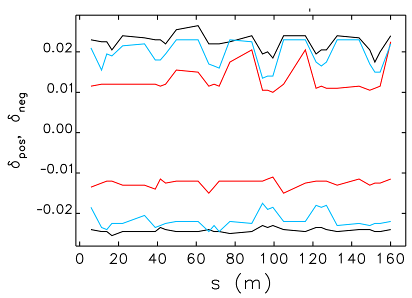

Figure 2: LMA for the initial model (black), after A:S2 power supply failure (red), and after correction (blue).

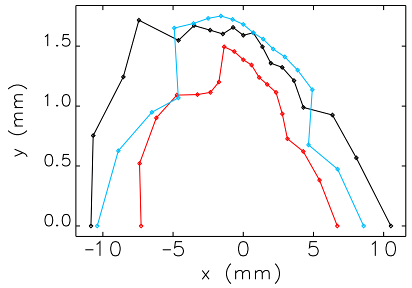

Figure 3: Dynamic acceptance for the initial model (black), after A:S4 power supply failure (red), and after correction (blue).

Table 1: Optimization Results for All Sextupole Families

	Before		After	
	Lifetime min	Inj. Effic. %	Lifetime min	Inj. Effic. %
No fault	510	95%		
A:S1	340	55	490	95
A:S2	100	65	350	95
A:S3	480	85	520	95
A:S4	90	30	270	95
B:S3	380	85	400	100
B:S2	100	60	300	90
B:S1	320	45	450	98

We compiled the optimization results for all sextupoles in Table 1, which gives the lifetime and injection efficiency after the sextupole power supply has failed and after the sextupole correction is applied. It also gives the initial lifetime and injection efficiency for the lattice with all sextupoles operating normally. We can see that S2 and S4 sextupoles have the biggest effect on the lifetime, and S4 has the biggest effect on the injection efficiency. S3 sextupoles have the least effect on both lifetime and injection.

EXPERIMENTAL TESTS

Since the beginning of operation, it has been APS policy to allow large user-requested beam steering. Over time the storage ring and beamlines have settled, and at some locations the steering has accumulated to several millimeters of orbit distortion. This orbit is called the “user orbit” and it deviates from the centers of magnets significantly. This would have been a big problem for the storage ring optics, but fortunately the APS has separate power supplies for all quadrupoles that allow for optics correction. As long as the optics is regularly corrected, there seems to be no significant negative effects from operating on a significantly non-zero orbit.

However, this large orbit creates additional difficulties when a sextupole turns off, and it also makes testing of the sextupole correction more complicated. To minimize the effect of sextupole changes on the storage ring optics due to non-zero orbit in sextupoles, we tested with sextupoles where the orbit deviation from the magnet centers was not large. And even after that, the sextupole changes give significant coupling changes.

We used the following procedure for the tests:

1. Set sextupole under test to 0.
2. Correct betatron tunes using quadrupoles, then correct emittance ratio using skew quadrupoles.
3. Record lifetime and injection efficiency.
4. Apply sextupole correction.
5. Repeat betatron tune and emittance ratio correction.
6. Record lifetime and injection efficiency.

Several sextupoles were tested. Since the tests were performed at different times, for each test we give the initial lifetime and injection efficiency. The results of the tests are shown in Table 2. We can see that sextupole correction really improves the lifetime and somewhat improves the injection efficiency. What differs from our simulation results is that injection efficiency does not suffer as significant a decrease as in simulations. We think this is because in simulations we increased the oscillation amplitude of the injected beam by 2 mm in order to allow for better optimization.

Figure 4 shows measured dynamic aperture for a test of another sextupole A:S3. Here we see that sextupole correction does increase the dynamic aperture. However, looking at the results in Table 2, we should not expect significant decrease in the dynamic aperture since the injection efficiency for A:S3 sextupole drops only by a few percent in simulations. Based on these few tests, we can say that in general, the sextupole optimization allows us to improve the storage ring performance in the case of a failed sextupole power supply. But in the details, there are some discrepancies between simulations and experiment.

Table 2: Experimental Results for Different Sextupole Tests

Sextupole	State	Lifetime min	Inj. Effic. %
A:S4	Initial lattice	440	85
	After failure	230	60
	After correction	330	75
A:S2	Initial lattice	550	80
	After failure	430	70
	After correction	550	80
B:S2	Initial lattice	540	80
	After failure	390	75
	After correction	440	75

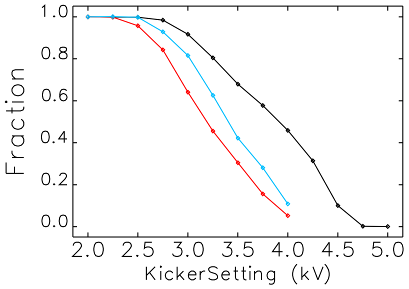

Figure 4: Measured dynamic aperture: initial conditions (black), after A:S3 set to zero (red), and after sextupole correction (blue).

CONCLUSION

We have shown that in a situation where one sextupole power supply turns off during top-up operation, decreasing lifetime and injection efficiency as a result, we can partially recover the lifetime and efficiency by properly adjusting nearby sextupoles. We used tracking to simulate injection and lifetime, and a genetic optimizer to find the best solution for nearby sextupoles. We performed experimental tests that confirmed the improvements in general; however, some discrepancies still exist in the details.

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