SEARCH FOR NONLINEAR BEAM DYNAMICS CAUSES OF LIFETIME REDUCTION AT THE APS STORAGE RING*

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Abstract

During an operating period in which a sextupole unknowingly connected with the wrong polarity resulted in reduced beam lifetime, a list of machine physics experiments and simulations were developed to identify possible gradient errors of one or more sextupole magnets. We tried tune dependence on orbit, response matrix measurements at different momenta, sector-wise chromaticity measurements, empirical search with sextupole harmonics, and guidance from tracking simulations. The practicality of each will be discussed.

INTRODUCTION

The lifetime of the stored beam at the Advanced Photon Source was reduced suddenly by ∼25% after a shutdown (Jan 2007). After checking the more obvious causes, such as reviewing work done during various shutdowns, checking vacuum apertures using beam bumps, measuring impedances, checking lattice symmetry by correcting optics, and visually checking recently-modified sextupole poles, we concluded that the reduction in beam lifetime (and momentum aperture) was due to some unknown lattice nonlinearity, say, a bad sextupole magnet coil. We developed and evaluated several beam-based methods that can be applied to such problems in the future, either at APS or elsewhere. (The final determination occured in Feb 2008 when we found that sextupole power supply S27B:S3 was connected backwards at the power supply in Jan 2007; this was ironically discovered by looking inside a power supply cabinet, rather than through our methods.)

We will describe each measurement and comment on its utility. In general, the measurements reflect the reversed-polarity sextupole S27B:S3, and hindsight analysis will be applied. The methods described below are generally available at other light sources. We are aware of the more sophisticated work in [1, 2] on Hamiltonian-term analysis from beam position monitor (BPM) histories. This requires a large set of turn-by-turn BPMs around the ring and the ability to extract higher-order tune amplitudes from the histories, which is generally unavailable at older light sources.

SECTOR CHROMATICITY CHANGE

The chromaticity change ($\Delta\xi_x$,$\Delta\xi_y$) due to malfunctioning of one sextupole can be calculated. Given a chromaticity measurement accuracy of about 0.25 unit. The list of individual sextupole contributions in Table 1 indicates we may only be able to detect ∼ 50% relative error (depending on the sextupole). A sextupole of family S3 was actually reversed, so we would have seen a change of -0.3 in x and -1.8 in y. Since the sextupole connection error was done in a shutdown, the net change of chromaticity was not noticed during the start-up week as the sextupole families may have been empirically adjusted without further thought.

Table 1: Chromaticity Contributed by Individual Sextupoles

Sextupole	$\Delta\xi_x$	$\Delta\xi_y$
S1A:S1	0.5	-0.49
S1A:S2	-0.13	0.72
S1A:S3	-0.15	0.9
S1A:S4	1.7	-1

We developed a method that locates the sector of a possible bad sextupole by directly measuring the chromaticity contribution of each sector's sextupoles. The steps are: a) measure chromaticity with nominal conditions (chromacitity is measured by fitting tune measurements of five rf frequency settings of range ± 100 Hz), b) ramp down sextupoles for one sector, c) remeasure chromaticity, d) turn sextupoles back on with no standardization, and e) repeat for other sectors. If the chromaticity in step c) in one sector differs from that of other sectors then we might have a bad sextupole there. A few hours per week were dedicated for this slow measurement. We stopped at sector 24 (out of 40) when the bad sextupole was discovered by other means. The method is slow and moderately accurate, depending on the sextupole location.

BEAM BUMP THROUGH SEXTUPOLE

This method uses tune measurements to determine whether a horizontal steering through a selected sextupole results in a predicted tune shift. Tune measurements (using one measurement plane, say x) are made under four conditions: a) nominal steering with nominal sextupole strength, giving ν_1; b) horizontal bump with nominal sextupoles, giving ν_2; c) nominal steering with sextupole ramped down to zero, giving ν_3; and d) same bump with sextupole ramped downm, giving ν_4. The bump may contain more than one sextupole, but only one is varied, so that the effect of the additional sextupoles is removed by subtracting the tunes. Also, we need to ensure that the beam energy is not changed by the bump. The bump is created by global orbit control tools and must be customized for each sextupole under test. The effect of the sextupole normalized gradient

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error ΔK_2 is

$$(\nu_2 - \nu_1) - (\nu_4 - \nu_3) = \frac{\beta_x}{4\pi} \Delta x \Delta K_2 L, \qquad (1)$$

where β_x is the horizontal beta function at the sextupole (determined with 1%-2% accuracy); Δx is the imposed horizontal bump at the sextupole under test, known to about the same relative accuracy; and L is the sextupole effective length.

In a variant of this method the bump can be replaced with global orbit without additional processing because the orbits through other sextupoles are taken into account with the tune substraction. The advantage is that bump configurations don't have to be customized for each sextupole. The processing can also include opposite-bump data for increased accuracy. The method is slow in general, but potentially accurate. However, the remnant field of the sextupole under test is not taken into account and is unknown in general. We only measured a handful of sextupoles with this method, as we couldn't understand the discrepancies with prediction of the first sextupoles tested that were known to be good. Table 2 show the results for six sextupoles in the bump method.

Table 2: Measurement of sextupole gradient with beam bump method using x and y tune changes. The units of K_2 are 1/m^2. The last column is the model value.

Sextupole	ν_x +1 mm / -1 mm	ν_y +1 mm / -1 mm	Model
S1A:S1	6.9 / 6.7	7.0 / 6.9	10.1
S1A:S2	-12.4 / -14.4	-15.0 / -15.5	-22.1
S1B:S2	-20.2 / -21.8	-18.8 / -18.9	-22.1
S1B:S1	9.0 / 9.2	8.5 / 8.7	10.1
S40B:S2	18.5 / -17.7	-18.5 / -18.0	-22.1
S40B:S1	8.3 / 8.1	8.1 / 8.5	10.1

LOCAL CHROMATICITY BY RESPONSE MATRIX FITTING

The local chromaticity is a series of positive and negative pulse-like functions along the circumference, i.e., $(\beta/4\pi)(K_1 - K_2\eta)$, where β is the betatron function of the plane of interest, K_1 is the normalized quadrupole strength, K_2 is the normalized sextupole strength, and η is the horizontal dispersion. The net chromaticity over a segment of the lattice can be determined through the phase advance difference between points in the lattice. For sextupole problems, we look for variations in the $K_2\eta$ term from sector to sector. This method [3] is inspired from LEP measurements of BPM phases [4]: a) for several rf frequencies (say, three), measure the BPM-corrector response matrix, b) obtain from three optics models the phase advance along circumference, c) fit $\phi_{x,y}(s)$ vs $\delta(= \Delta p/p)$, whose slope $d\phi_{x,y}(s)/ds$ gives the chromatic phase advance. Optionally, step d), the perturbation in local chromaticity is detected by plotting $d\phi_{x,y}(s)/d\delta - d\phi_{x,y}(s - L)/d\delta$, where L is the optics period length, or some other short distance.

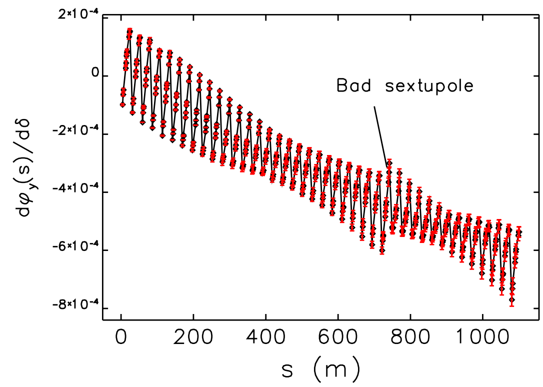

Figure 1: Chromatic phase advance.

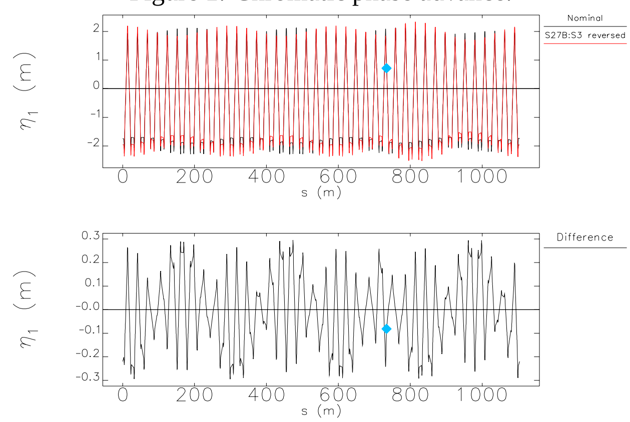

Figure 2: Nonlinear dispersion calculation from ideal model plus a sextupole reversed.

Figure 1 shows the quantity $d\phi_y(s)/d\delta$ from the response matrix data. We had taken the raw data but, unfortunately, not analyzed it until after the problem was resolved. The spike in the data shows the location of the bad sextupole. The method would have detected 25% of the sextupole setting.

This method is fast and accurate though it requires much postprocessing. Though the method can't take credit for detecting our problem this time, it can be used in the future.

SECOND-ORDER DISPERSION

Reference [5], p. 106, gives a differential equation for the nonlinear dispersion:

$$\eta_1'' + K_1\eta_1 = -h + \frac{1}{2}K_2\eta_0^2 + \ldots, \qquad (2)$$

where we define $\eta(s) \approx \eta_0 + \eta_1\delta$, and h is the curvature of design orbit. The main driving term is the bending magnet curvature h. The next important term is due to sextupoles. A measurement of the second-order dispersion in the presence of some sextupole irregularity would reveal some small oscillation superimposed on a periodic component. Figure 2 shows a model η_1 for a reversed sextupole.

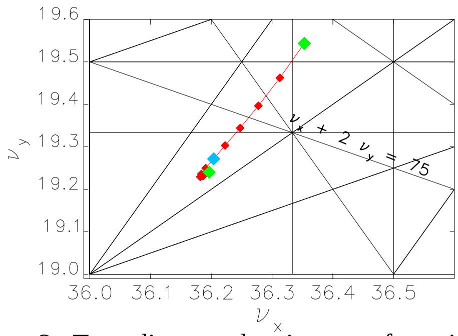

Figure 3: Tune diagram showing tune footprint for ±2% momentum range.

This method would be very fast to use. In practice, it would be difficult to identify a single sextupole error since a moderate linear optics error easily masks the sextupole error signal. Thus this method is useful only if we had corrected the first-order dispersion before the sextupole error occured and had BPM gains properly calibrated.

SEXTUPOLE HARMONIC KNOBS

The tune diagram in Figure 3 shows a crossing of the $\nu_x + 2\nu_y = 75$ line, which is driven by normal sextupoles. Possibly the lack of symmetry enhances the particle loss at that line. In this example, the nominal tunes are $\nu_x = 36.21$, $\nu_y = 19.27$, and the chromaticities are +4.0 and +6.5, in x and y planes, respectively.

We applied a sextupole harmonic knob to the problem lattice for correcting that particular sextupole resonance. At some amplitude and phase adjustment the lifetime for our standard fill pattern increased from 250 to 340 minutes. We found that the momentum aperture was not increased, however, which was puzzling.

We could not reproduce the above improvement in simulations of a lattice with symmetry broken by a turned-off sextupole picked at random. Simulation studies [6] with lattice models showed that a sextupole harmonic knob had much less effect on a symmetric lattice with one bad sextupole than on an ideal lattice with general errors added.

In hindsight, we know that the lattice suffered from a single sextupole. Simulation says that we shouldn't have been able to improve momentum aperture anyway, which was consistent with our measurement.

Though this fast method doesn't identify bad sextupoles, it has potential in recovering lifetime loss in general.

SEXTUPOLE FAMILY OPTIMIZATIONS

The APS ring has four sextupole families. Thus for a given chromaticity there are two free parameters for optimizing the dynamic aperture (DA), the momentum aperture (MA), or a mixture of both. Performing an empirical, constrained, four-dimensional search on the actual ring is difficult because chromaticity, x-y coupling, and tunes would have to be corrected with some effort for each iteration step. Thus optimal solutions would have to be found

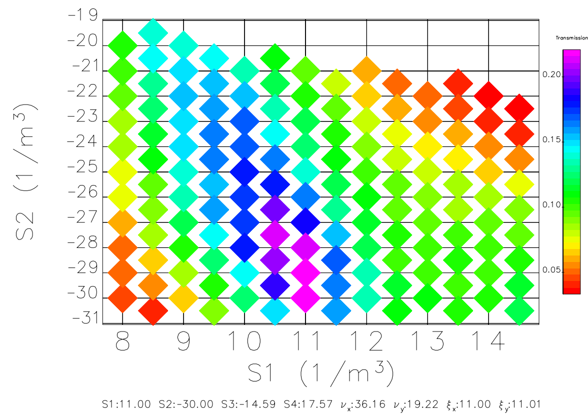

Figure 4: Survival intensity plot.

in simulation instead, and installed in the working lattice. We optimized DA and MA by calculating the transmission of a group of particles with large 6D phase space [7]: ± 10 mm in x, ± 2 mm in y, ± 2.5% in δ. Figure 4 shows the survival intensity plots where families S1 and S2 are taken as independent variables and S3 and S4 are adjusted for the chromaticities.

The optimization was done with lattices with large and small optical errors. Solutions with large errors have high S1 values (∼14) while solutions with small errors (Figure 4) have lower S1 values (∼11). Thus the optimum sextupole settings depend on the magnitude of errors. We tested both solutions in machine studies. The solution for large errors improved the beam lifetime, while the solution for small errors decreased the injection efficiency and the lifetime. We concluded that there is a strong error in the ring. At this point we finally checked the polarities of the sextupoles, and found the sextupole with reversed polarity.

CONCLUSION

Much work was done to identify a bad sextupole using various beam-based methods. Also much work was done during this one-year period in maximizing lifetime (and DA) with sextupole optimization, and injection trajectory optimization. The response matrix method for finding a bad sextupole is the preferred one.

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