LOCAL CHROMATICITY MEASUREMENT USING THE RESPONSE MATRIX FIT AT THE APS*

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Abstract

The response matrix fit is routinely used at the Advanced Photon Source (APS) for linear optics correction [1]. The high accuracy of the method enables us to measure the variation of betatron phase advance around the ring with rf frequency. This variation can be used to calculate local chromaticity. Such measurements were first performed at the APS at the moment when a sextupole was mistakenly connected with the wrong polarity. Local chromaticity calculations clearly pointed to the location of the sextupole error. Results and details of the measurements are reported and discussed.

INTRODUCTION

During part of 2007 and the beginning of 2008 APS operated with unusually short lifetime. An extensive investigation was performed during that time [2] that led us to believe that the sextupole distribution symmetry was broken.

In order to confirm it, we performed local chromaticity measurements using the response matrix fit. Chromaticity of the lattice is usually measured as the dependence of betatron tunes on rf frequency. Following this, local chromaticity can be measured as the dependence of local betatron phase shift on rf frequency. To obtain the local betatron phase shift we use a response matrix fit that provides us with the linear model of the lattice. The model can then be used to calculate betatron phases. This measurement is similar to the local impedance measurement we performed earlier [3]. For local impedance measurement we used the fact that lattice focusing is different for different single-bunch currents; for local chromaticity we would use the fact that the focusing is different for different beam momenta (or rf frequency). The idea of local chromaticity measurement is not new; one of the first measurements was done at CERN using fast kicker and BPM beam history [4].

Data on local chromaticity were taken in November 2007 but were not analyzed until after the problem was corrected three months later by visually inspecting the sextupole power supplies. Even though the method can't take credit for solving that lifetime problem, it can be used in the future for similar diagnostics.

MEASUREMENTS

The APS storage ring has 40 nearly identical sectors. Each sector consists of two dipoles, ten quadrupoles, and seven sextupoles. There are also eight horizontal and eight vertical steering magnets and nine to eleven beam position monitors (BPMs) per sector. The response matrix fit is used routinely for optics corrections after lattice or operation mode changes. In order to limit the duration of the response matrix measurement and the size of the response matrix derivative, we usually use only 27 horizontal and 26 vertical correctors and all available BPMs.

We measured the response matrix for a set of three rf frequencies (changes of frequency): –300 Hz, 0 Hz, and +300 Hz. We used a 324-bunch fill pattern for longer lifetime and hybrid mode sextupole settings for higher total chromaticity (chromaticity for the hybrid mode is +11 in both planes in order to achieve the high single-bunch accumulation limit).

The measurement processing consists of two steps: perform a response matrix fit for each measurement, the result of which is the Twiss file with beta functions and phases corresponding to the linear model of the ring; then analyze betatron phase changes across these Twiss files to calculate local chromaticity.

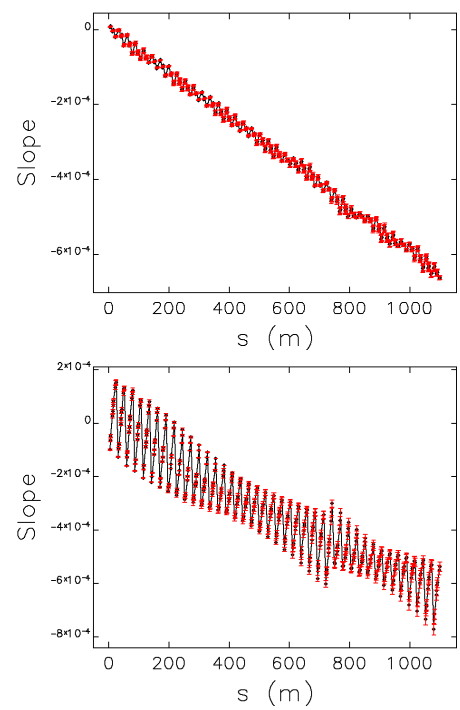

Figure 1: Betatron phase slope with rf frequency – top is horizontal plane, bottom is vertical plane.

Figure 1 shows the betatron phase advance slope along the circumference of the machine. It was calculated in the following way: for each lattice element we collected betatron phase from the three Twiss files corresponding to different rf frequencies and performed a straight-line fit using these three points. The resulting slopes are plotted

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in Fig. 1. Error bars (red) come from the straight-line fit. One can see that nothing out of the ordinary appears on the plot of the horizontal phase slopes. However, on the vertical phase plot, there is a jump at around 730 m, which corresponds to sector 27.

To localize the chromaticity perturbation, we calculated the phase difference between each point on the phase slope plot and a point exactly one sector in front of it. Figure 2 shows the vertical phase slope difference plot. We can see a spike around sectors 27 and 28. The first step of the spike corresponds to the S27B:Q3 quadrupole. That means that the chromaticity perturbation is located right in front of that quadrupole. It is exactly where the reversed sextupole was found.

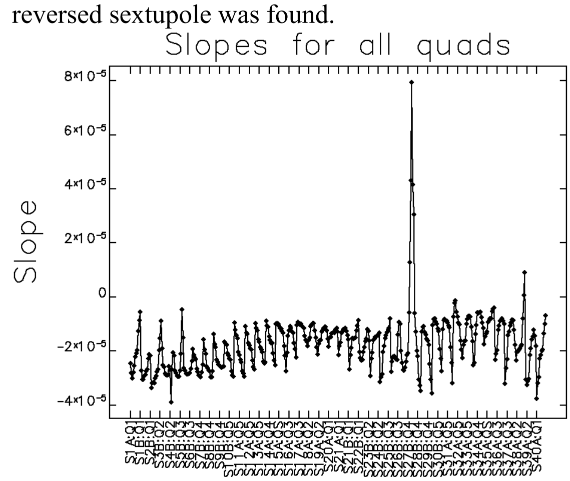

Figure 2: Slope difference between each element and a point one sector in front of it.

Local betatron phase slopes can be used to calculate local chromaticity the same way the tunes are used to calculate total chromaticity. We used the usual formula to calculate chromaticity from the phase slope:

$$C_z = \frac{1}{2\pi} f_{rf} \cdot \alpha_c \cdot \frac{d\psi_z}{df_{rf}},$$

where f_{rf} is rf frequency, α_c is the momentum compaction factor, and $d\psi_z/df_{rf}$ is the local phase slope calculated above. Figure 3 shows the per-sector chromaticity, which was calculated the following way: we used the slope difference from Fig. 2 and averaged all elements within a sector. This represents a running average per-sector chromaticity with a one-sector averaging window. The oscillations of the horizontal and vertical chromaticity are caused by beta function and dispersion beating.

Improving the Sensitivity of the Method

A sextupole with reversed polarity is a big perturbation to the sextupole distribution. In order to investigate the sensitivity of the method, we performed a measurement of the local chromaticity with the K2 value of one sextupole reduced by 5 1/m^2. Depending on the sextupole family, this corresponds to 20% to 50% of the total sextupole strength. In order to increase the accuracy, five measurements were performed within the same rf frequency range of ±300 Hz. Unfortunately, this range cannot be easily increased because the APS lattice becomes unstable above +300 Hz. We have performed the same analysis of phase advances described above and were not able to clearly identify the location of the test sextupole.

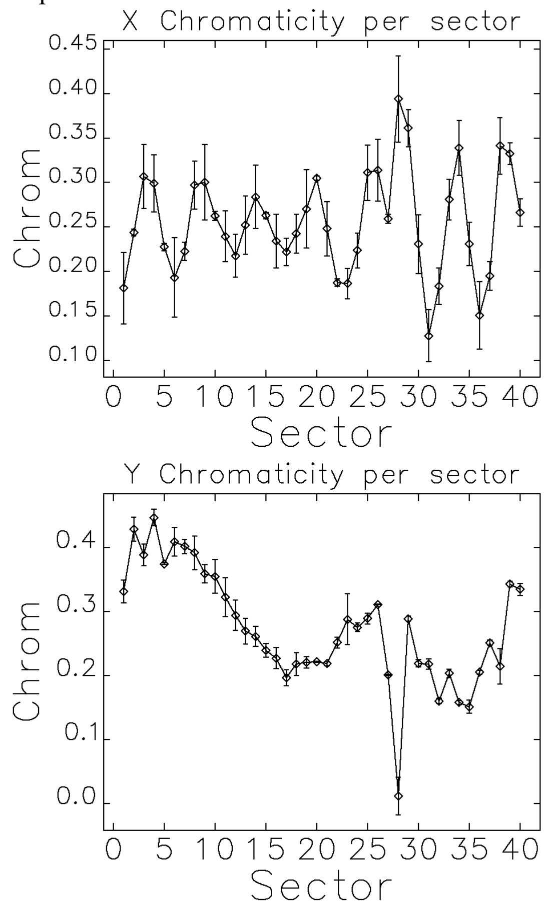

Figure 3: Local chromaticity per one sector. Top plot is horizontal chromaticity, bottom plot is vertical chromaticity.

We tested a few other approaches to try to improve on the sensitivity of the calculations. One approach is to fit the phase-slope curve like the one shown on Fig. 1 using a small number of quadrupoles (usually one or two per sector). This method avoids the quadrupole ambiguity problem of the response matrix fit. But the phase-slope curves are noisy, which makes a search for a small perturbation difficult. Another approach we tried consists of two steps. First, the response matrix fit of the measurement at nominal rf frequency is performed varying all 400 quadrupoles to achieve the best fit accuracy. Then, since for the off-momentum measurements the only focusing changes come from sextupoles, we performed a response matrix fit of those measurements, varying artificial quadrupoles at the location of the sextupoles. Because the sextupoles are located everywhere around the machine, we had to use many quadrupoles, and this method suffered from the same quadrupole ambiguity problem.

We were able to achieve the best results when we modified the latter approach. For each off-momentum measurement, we performed a response matrix fit on the orbit distorted due to rf frequency change (in real calculations using elegant [5], this was done by varying path length DZ of an artificial drift-space element at the end of the lattice [6]). In this case the existing sextupoles of the lattice already took care of the focusing changes due to orbit change. Therefore, one can reduce the number of focusing elements in the fit – we used 120 artificial quadrupoles. Also, quadrupoles obtained in the fit correspond only to additional focusing that is not represented by a normal sextupole. For most of the sextupoles the additional quadrupole focusing is supposed to be zero except for the sextupoles with errors. This improves signal-to-noise ratio of the method.

The processing of the measurements was as follows. First, the response matrix fit is calculated for every measurement (we used three quadrupoles per sector placed at sextupole locations). This resulted in five sets of quadrupole *K1* values, each corresponding to a different rf frequency. Then for each quadrupole, we calculated the *K1* slope with rf frequency. Figure 4 shows *K1* values and the slope fit for the test sextupole. The slopes can be used to calculate corresponding sextupole strength:

$$K2 = -\frac{dK1}{df_{rf}}\frac{\alpha_c f_{rf}}{\eta},$$

where $dK1/df_{rf}$ is the *K1* slope, and η is horizontal dispersion. Figure 5 shows the resulting *K2* values. The top part of this figure shows all sextupoles. One can clearly see the strongest spike that corresponds to the test sextupole. Sextupoles from different families are located at different dispersion and beta functions within a sector and can have different effects on the response matrix fit. Therefore, it might be more reasonable to consider sextupole strength spikes within the same sextupole family. The bottom part of Fig. 5 shows the sextupoles of only one family, S1. Here the test sextupole stands out more convincingly. On the top part of Fig. 5 one might also notice three more spikes of a lesser value (about –0.2). They all correspond to the S2 family of sextupoles. This family was mechanically modified a few years ago to increase its strength. So these spikes might be real sextupoles with problems or they might just be the noise of the measurement. We will further investigate this question.

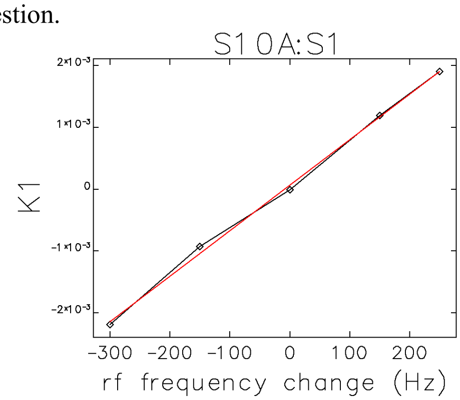

Figure 4: Results of the response matrix fit for the test sextupole and the linear fit (red line).

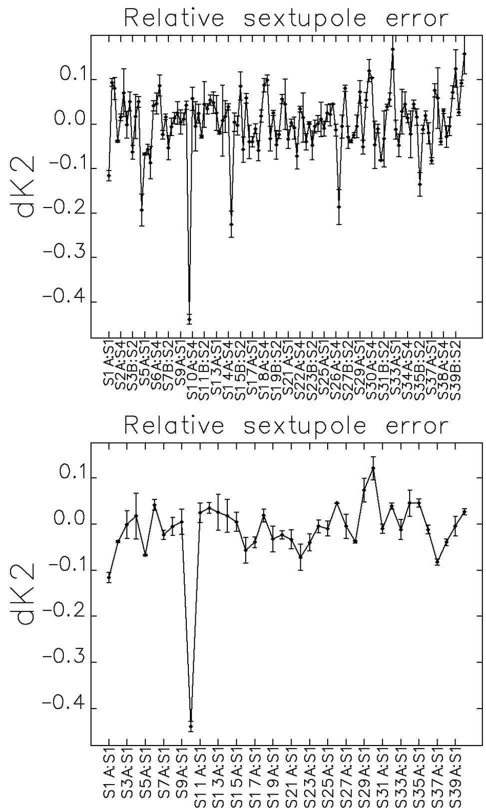

Figure 5: Measured corrections to sextupole K2 values. Top plot – all sextupoles used in the response matrix fit, bottom plot – only the S1 sextupole family; the test sextupole clearly stands out.

CONCLUSION

We have implemented local chromaticity measurement using a response matrix fit at different rf frequencies. We have used this method to diagnose a sextupole mistakenly connected with the wrong polarity. The data were not analyzed until the problem was solved by visual inspection of power supplies, but we have shown that this method can be used in the future for sextupole diagnostics.

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