ACCURACY AND STABILITY OF LATTICE CORRECTION FOR THE UPGRADED APS*

V. Sajaev†, A.J. Dick, L. Emery
Argonne National Laboratory, Argonne, IL, USA

Abstract

A well-corrected lattice is essential for the performance of any modern synchrotron light source. Beyond the standard motivations – such as preserving optimized nonlinear dynamics and maintaining sufficient dynamic and momentum acceptance – accurate lattice correction is particularly important in Advanced Photon Source Upgrade (APS-U) for achieving the predicted emittance reduction associated with insertion device radiation. In APS-U, lattice characterization relies on response matrix fitting. Simulations performed during the design phase indicated that the achievable accuracy of such measurements would be limited to the few-percent level, thereby constraining the ultimate lattice correction precision. This paper presents the typical results of the APS-U lattice correction, examines approaches to improving lattice measurement accuracy, and discusses the long-term stability of the corrected lattice.

INTRODUCTION

The Advanced Photon Source (APS) currently operates with a design natural emittance of 42 pm · rad and routinely provides an electron beam with a measured emittance of 30 pm · rad in full coupling mode [1]. With insertion devices (IDs) set to typical user gaps, the emittance is further reduced to about 25 pm · rad. This paper aims to document how routine operational activities – such as adjusting ID gaps, orbit steering for beamline optimization, and magnet conditioning following maintenance – affect the lattice of a fourth-generation light source.

LATTICE DETERMINATION ACCURACY

Before analyzing the lattice changes over time, we first examine the accuracy of lattice determination. In storage rings, the lattice is typically reconstructed using either response matrix (RM) fitting [2] or turn-by-turn betatron motion analysis [3]. RM fitting is generally considered the more reliable approach, and it is therefore adopted in this work.

There is no direct method to quantify the accuracy of lattice determination obtained from an RM fit. Instead, commissioning simulations provide a practical benchmark. In these simulations, realistic machine errors are introduced and subsequently corrected, after which the lattice is reconstructed using a simulated RM fit [4]. Because both the "true" lattice and the reconstructed lattice are known, the accuracy of the RM-based determination can be evaluated directly. By repeating this process over many error realizations, one obtains a statistical estimate – typically expressed as an rms deviation – of the lattice determination accuracy. The accuracy achieved in real operation is unlikely to exceed that observed in simulation.

Commissioning studies [4, 5] indicate that RM fitting typically achieves lattice determination accuracy at the level of a few percent rms. The origin of this limitation is not fully understood. Since resolving lattice drift in routine operation requires the highest possible accuracy, this motivates a closer examination of the RM fitting procedure and potential strategies for improvement. One possible contributing factor is the residual error in the RM fit itself.

Modification of RM Fit to Include Sextupole Effects

It is expected that the dominant contribution to lattice distortion arises from non-zero orbit offsets in sextupoles, rather than from intrinsic quadrupole strength errors. However, the RM fitting program used at APS (`SRLOCOFitting`) has traditionally relied only on quadrupole strength errors and tilts to reproduce the measured response matrix. This approach is based on experience with the pre-upgrade APS, where the number and distribution of quadrupoles were sufficient to effectively represent all focusing errors – including those originating from orbit offsets in sextupoles – using quadrupole variations alone. This assumption has also been applied in APS-U lattice correction until recently. Here, we examine whether explicitly including sextupole-induced focusing improves lattice determination accuracy.

The most direct way to incorporate focusing from orbit offsets in sextupoles within `SRLOCOFitting` is through the "special variables" option, which allows arbitrary parameters to be varied with user-defined rules. This option allows to directly include the horizontal and vertical offsets of sextupoles as fit variables. However, varying these offsets during the fit alters the closed orbit at each iteration, thereby modifying the response matrix itself and complicating convergence.

To avoid this issue, we instead introduce zero-length multipole elements adjacent to each sextupole and vary their strengths in the fit. The multipole components model the quadrupole and skew-quadrupole components arising from horizontal and vertical orbit offsets, respectively. This follows the existing treatment of focusing dipole tilts in `SRLOCOFitting`, where multipole elements are used to represent quadrupole tilts without generating vertical orbit.

Including these sextupole-related focusing multipoles resulted in a modest improvement in the response matrix fit, reducing the residual error by approximately 20%. How-

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† sajaev@anl.gov

ever, this improvement did not translate into better lattice determination accuracy.

An important outcome of this extended model is a significant reduction in the inferred quadrupole strength errors near sextupoles, confirming that the dominant source of apparent focusing errors is orbit offsets within sextupoles. Figure 1 (left) shows the standard deviation of K1 errors obtained from the response matrix fit, grouped by quadrupole family, with and without sextupole-related fit variables. The quadrupole families adjacent to sextupoles are Q3, Q4, Q5, and Q6. Figure 1 (right) presents the corresponding average K1 errors.

Several quadrupole families exhibit non-zero average K1 errors; most notably, the FODO module magnets – Q8, M3, and M4 – show significant systematic focusing offsets. The origin of these non-zero average errors remains unclear.

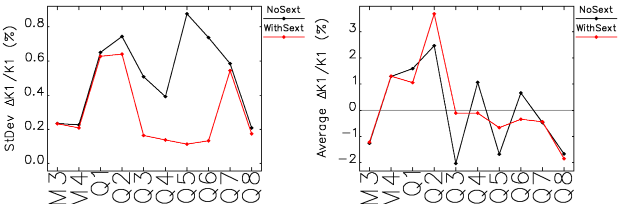

Figure 1: Left: Standard deviation of quadrupole K1 error by quadrupole family obtained from the response matrix fit with (red line) and without (black line) sextupole focusing errors. Right: Average K1 error by family.

Lattice Errors with Simplified Error Sets

The realistic error sets used in commissioning simulations include magnet strength and tilt errors, magnet misalignments, BPM and corrector calibration and tilt errors, as well as BPM offsets. The magnitude of these errors is sufficiently large that simulating machine performance typically requires a full commissioning-like procedure: establishing a closed orbit and correcting the lattice to a reasonably low level of distortion. This process is both complex and time-consuming. As an alternative, simplified error sets are sometimes employed. These are constructed to be small so that, even without correction, they produce lattice distortions comparable to those of a realistically perturbed machine after correction. Such simplified models typically include reduced magnet strength and tilt errors and neglect magnet misalignments.

To investigate lattice determination accuracy by the response matrix fit, we performed simulations using these simplified error sets. In addition to reduced magnet strength and tilt errors, BPM and corrector calibration and tilt errors were included at the same levels as in the realistic error sets. The magnitude of the magnet strength errors was chosen such that the uncorrected lattice distortion was of the order of 5 to 10 %. As in the commissioning simulations, the orbit response matrix was computed and used in the RM fit, and the reconstructed lattice was compared to the “true” lattice used to generate the response. This procedure was repeated for many realizations with randomized errors.

The results show that lattice determination accuracy is significantly improved for the simplified error sets. Figure 2 presents the cumulative distribution function (CDF) of the rms relative beta-function error for 100 realizations. The simulations indicate that, for realistic error sets, the median beta-function determination accuracy is 2.3 % in the horizontal plane and 1.6 % in the vertical plane, whereas for the simplified error sets it improves to 0.12 % and 0.38 %, respectively. The underlying reason for this substantial improvement is not yet fully understood; however, these results demonstrate that response matrix fit can achieve high lattice determination accuracy under favorable conditions.

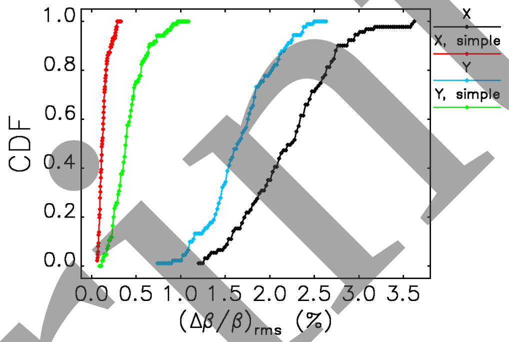

Figure 2: CDF of beta function determination accuracy by the RM fit calculated over 100 error sets. Comparison of the realistic and simplified error sets is shown.

Lattice Determination Reproducibility

Since response matrix fit can achieve high lattice determination accuracy under certain conditions, an important question arises: is the reduced accuracy observed with realistic machine errors primarily due to random effects, or does it reflect a systematic limitation of the model?

To address this, we measured the orbit response matrix five times and performed independent RM fits to reconstruct the lattice for each dataset. The results show excellent reproducibility. Figure 3 presents the standard deviation of the beta functions and dispersion at each BPM across the five reconstructed lattices. The rms reproducibility of the beta function is better than 0.3 %, while the dispersion is reproduced to within 0.3 mm rms.

This high level of reproducibility indicates that response matrix-derived lattices are highly stable. In practice, this implies that week-to-week variations in the beta function can be trusted at better than the 1 % level. At the same time, it suggests that the lattice determination errors predicted by commissioning simulations are dominated by as-yet-unidentified systematic effects. Further investigation of these effects is beyond the scope of this work.

LATTICE VARIATION RESULTS

APS operates on a six-days-per-week user schedule, with one additional day allocated for maintenance and machine studies. During routine user operation week, beam losses occur several times, and magnet conditioning may be performed during recovery. Conditioning can also take place

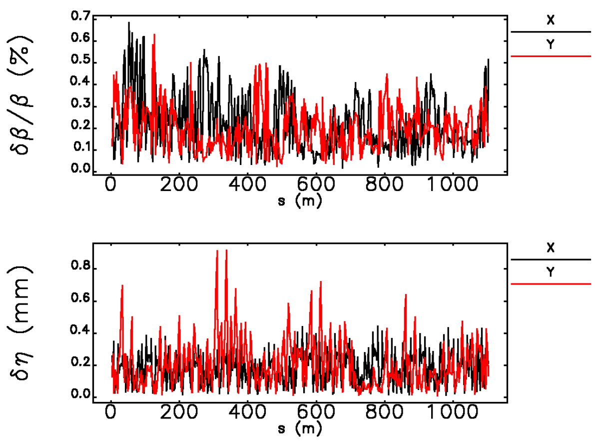

Figure 3: Measured beta function (top) and dispersion (bottom) reproducibility. Each point is rms over five RM measurements.

during maintenance periods, depending on the work carried out. Magnet conditioning can lead to changes in the lattice. In addition, orbit steering to optimize beamline performance and adjustments of insertion device (ID) gaps are routinely performed during user operation. While these effects are expected to be small, they may also contribute to lattice variations.

To assess day-to-day lattice stability, we measured the orbit response matrix immediately before and after each six-day user run over a three-month period. Prior to this campaign, lattice measurements and corrections were not performed regularly, based on the assumption that the lattice would remain sufficiently stable.

The response matrix was measured using 20 correctors per plane, with ID gaps set to their current user configurations. The RM fit was performed with a fixed setup to minimize systematic variations in the fitting procedure. Figure 4 shows the evolution of the beta function over time: the black curve represents the rms deviation from the ideal lattice, while the red curve shows the rms difference relative to the previous measurement.

The results indicate that the typical rms lattice deviation from the ideal lattice is about 2 %. This is consistent with the applied correction strategy, where quadrupole adjustments are intentionally limited to avoid over-correcting beyond the expected lattice determination accuracy. A notable increase in lattice error is observed on March 2 (black curve), which is attributed to orbit steering performed at that time to improve injection efficiency. The lattice remained in this perturbed state until it was corrected on March 25, after which it returned to a relatively stable condition. The measurement-to-measurement variation (red curve) remains at the 1 % level, except during periods involving significant interventions such as lattice corrections or major orbit adjustments.

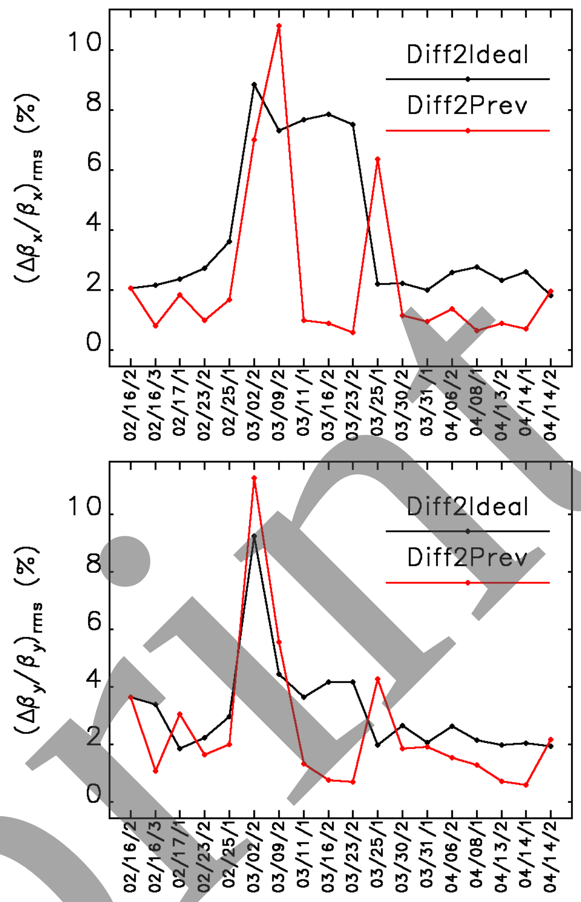

Figure 4: Week to week beta function variation. Black line – rms difference between the measured lattice and the ideal lattice. Red line – rms difference between two consequitive measurements.

SUMMARY

We have documented the week-to-week variation of the APS-U lattice. First, we evaluated the reproducibility of the lattice determined from response matrix fitting and found it to be significantly better than the lattice determination accuracy predicted by commissioning simulations. This suggests that the RM-based lattice reconstruction may be affected by unidentified systematic errors. Nevertheless, the high reproducibility indicates that response matrix fitting remains a reliable tool for tracking relative lattice changes over time.

Using this approach, we find that the typical week-to-week lattice variation is about 1 % rms, while the average deviation between the measured and ideal lattices is approximately 2 % rms. The observed variations are likely driven by magnet changes after conditioning and orbit changes associated with user-requested steering.

We also investigated whether lattice determination accuracy could be improved by explicitly including sextupole-induced focusing in the response matrix fit via additional multipole elements. While this approach reduced the residual fit error, it did not lead to any measurable improvement in lattice determination accuracy.

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