Lattice Model Calibration and Frequency Map Measurements at the ALS*

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Abstract

To understand the dynamics in an accelerator it is essential to have a good model representing its realistic lattice. One method used at the ALS to calibrate the linear (coupled) accelerator model is the analysis of orbit response matrices. Recently this method has been combined with frequency map techniques, both in tracking and experiment at the accelerator. Comparing the results of simulated and measured frequency maps shows how accurately the accelerator model describes the nonlinear beam dynamics. In addition measured frequency maps can serve as a model independent tool to evaluate the quality of a lattice. The measurements at the ALS clearly show the network of coupling resonances and the agreement with the simulation using the calibrated model is very good whereas the disagreement is large when using an ideal accelerator model.

1 INTRODUCTION

The Advanced Light Source (ALS) is a third generation synchrotron light source located at Lawrence Berkeley National Laboratory [1]. Similar to the situation at all other third generation synchrotron light sources the single particle dynamics is an important factor which contributes to several performance limitations. If the particle motion at large amplitudes is unstable, electrons scattered to these large amplitudes via collisions with gas particles (gas lifetime) or other electrons (Touschek lifetime) may be lost. Similarly, electrons injected at large amplitude may not be captured.

Table 1: Nominal ALS parameters.

Parameter	Description	
E	Beam energy	1.5–1.9 GeV
C	Circumference	196.8 m
ν_x	hor. tune	14.25
ν_y	vert. tune	8.20
ζ_x	hor. nat. chromaticity	-24.6
ζ_y	vert. nat. chromaticity	-26.7

To reach small equilibrium emittances third-generation light sources use strongly focusing quadrupoles. The resulting large chromatic aberrations have to be corrected with strong sextupole magnets in order to provide damping of the head tail modes. The sextupoles in turn generate geometrical and nonlinear chromatic aberrations, exciting resonances that can make the motion of the electrons unstable. If the lattice is periodic, many low order resonances are suppressed. The ALS magnetic lattice is constructed of twelve identical sectors.

* This work was supported by the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

2 MODEL CALIBRATION

To calibrate the linear model of the ALS an analysis of measured orbit response matrices (LOCO [2]) has been used for several years [3]. In the analysis all gradients (quadrupoles and offsets in sextupoles) can be determined with a relative accuracy of about $1 \cdot 10^{-3}$. In addition one gets relative gain factors of all correctors and all beam position monitors. The β-beating after a correction, based on the results of the model fitting, is small; about 2% in the horizontal and 3% in the vertical plane (peak). Recently LOCO has been modified to allow a model calibration of a complete, fully coupled machine model with reasonable computation time [4]. This allows the determination of localized coupling terms.

3 FREQUENCY MAP ANALYSIS

Resonances can lead to irregular and chaotic behavior for the orbits of particles, which eventually will get lost by diffusion to high amplitudes. To calculate the strength of a resonance usually a tracking code which numerically simulates the evolution of beam particle is employed [5].

The dynamics of the resulting 4-dimensional symplectic return map can be analyzed using Laskar's Frequency Map Analysis (FMA) method [6, 7, 8, 9, 10]. The FMA numerically constructs a map from the space of initial conditions to the frequency space. For each selected initial condition the particle motion is tracked numerically, and the trajectory is recorded turn by turn. Then a numerical algorithm based on a refined Fourier technique (see [9]) is used to search for a quasiperiodic solution. If the trajectory is regular, the KAM theorem (see [11]) requires that the motion is quasiperiodic, with two fundamental frequencies (ν_x, ν_y). In this case, the frequencies can be determined with very high accuracy since the algorithm converges like $1/T^4$ [9].

Moreover, the numerical algorithm always yields a quasiperiodic approximation of the trajectories, and therefore the map is numerically defined on the entire space of initial conditions [7, 8].

3.1 *Ideal Lattice versus Calibrated Machine Model*

Frequency maps provide a clear and intuitive view of the global dynamics of the complete phase space of the system. This can be seen in Fig. 1 where a frequency map for a grid of initial conditions (equidistant in betatron amplitudes) with tracking over 1000 turns is shown. This is about 1/20th of the damping time due to synchrotron radiation which has been ignored in the computations. In the lattice model the chromaticity (like in the real machine) is adjusted to be slightly positive using the two families of sextupoles. Besides the sextupoles, the lattice used for the calculation was ideal with a perfect 12-fold periodicity and a working point of $(14.25, 8.18)$. Due to the detuning with amplitude the betatron tunes change for particles with non-zero amplitudes. Initial conditions with only horizontal or only vertical amplitude correspond respectively to the lower-right and upper-left envelope of the plot. The lines appearing in the figure are resonances which show up as distortion of the frequency map. In addition chaotic zones appear corresponding to non-regular behavior of the frequency map. The color code is indicating the diffusion rate as defined by the change in betatron tune per revolution on a logarithmic scale.

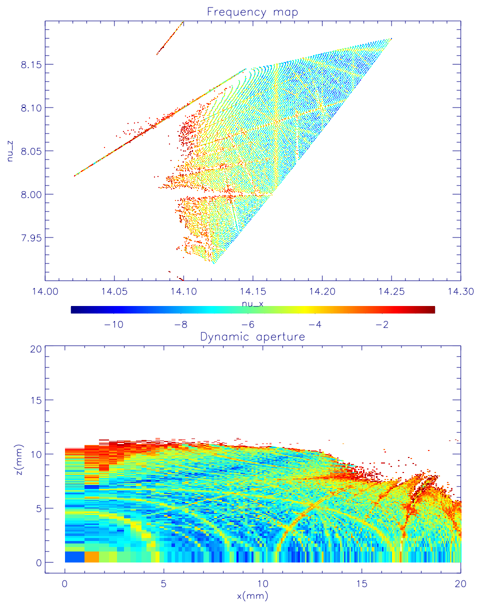

Figure 1: Frequency map of the ALS for an ideal lattice.

The errors of the real machine reduce the size of the regular region by destroying the 12-fold periodicity and exciting additional resonances. Fig. 2 shows a frequency map, where fitted linear (gradient and coupling) errors have been included in the model. The stable region in this case is significantly reduced in comparison with the ideal lattice. In addition the loss mechanisms are very different. In the ideal case particle loss is very fast (a few turns) and happens on high order, allowed resonances. For the calibrated model the loss is a slow diffusion (some thousand turns) on (intersections of) lower order resonances.

In order to determine, whether any of those two models represents the nonlinear dynamics of the ALS correctly, a measurement of a frequency map was carried out providing a picture of the global dynamics of the real beam [12].

4 EXPERIMENT

Two tools were used to perform the measurements at the ALS. First, there is a set of two single turn (600 ns) kickers ("pinger magnets"). Together, both pinger magnets are able to launch the beam simultaneously to variable horizontal

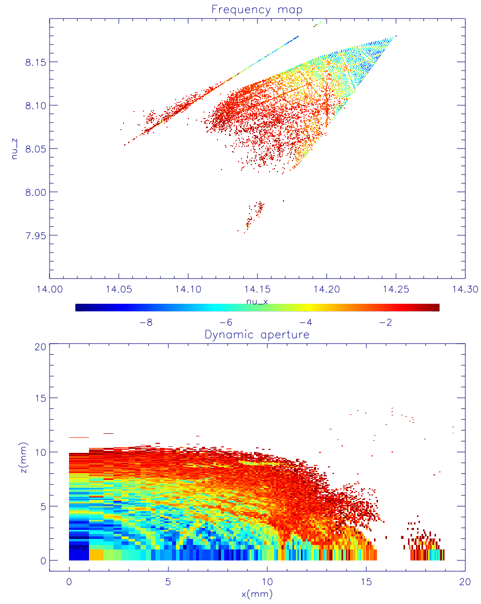

Figure 2: Frequency map of the ALS for the calibrated lattice model with measured errors.

and vertical amplitudes. The second tool is turn-by-turn beam position monitors (BPM). During an experiment, the ring is filled with a train of 40 consecutive electron bunches (to get better resolution of the BPMs). The total current is 10 mA ($4 \cdot 10^{10}$ electrons).

During each run, two sets of measurements are taken. First, an orbit response matrix is measured to calibrate the linear model. Then a set of turn-by-turn data is recorded for the frequency map. In order to obtain a regularly distributed image, the horizontal and vertical pinger strengths are set such that the squares of those strengths are evenly spaced. The data acquisition time for each point is about 20 seconds, or about 4 hours for the complete map.

For the first experiment we selected tunes and chromaticities close to the nominal conditions for user operation (compare Tab. 1). The linear lattice was measured and adjusted to make it as close to 12-fold periodic as possible (2-3% β-beating, 1% coupling). The frequency analysis was performed with 25 by 25 initial conditions (Fig. 3a). One clearly sees two strongly excited coupling resonances of 5th order which are 'unallowed' for 12-fold periodicity and do not show up in the frequency map for the ideal lattice. They are excited by small remaining gradient and coupling errors. This shows that the ideal lattice is not a good representation of the real machine. Moreover we found that a lattice model with random errors also did not agree well.

In order to check our calibrated lattice model, we calculated a frequency map based on the orbit response matrix data from the same day (Fig. 3b). The agreement of the two frequency maps is excellent. We therefore conclude that a model using nominal sextupole strengths and calibrated gradient and coupling errors is describing the nonlinear dynamics in the ALS very accurately.

In the future, we expect to reduce the measurement time for a frequency map, to make it available as routine online

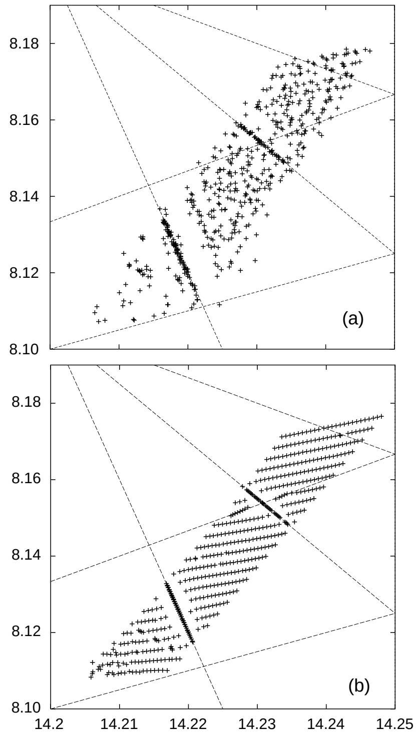

Figure 3: Experimental frequency map (a), and numerical simulation (b) for the ALS with its nominal settings. Resonances of order ≤ 5 are plotted with dashed lines.

monitor of the quality of the beam dynamics. As an illustration of the model independent diagnostic capabilities of experimental frequency maps, we set a slightly different working point ($\nu_x = 14.275, \nu_y = 8.167$). In this case, the measured frequency map (Fig. 4) shows several strong, intersecting (at $14.25, 8.125$) resonances. The intersection induces rapid diffusion of particles with corresponding reduction in injection efficiency and lifetime.

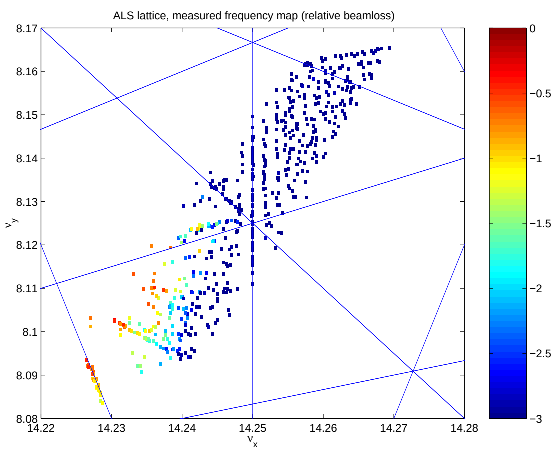

Figure 4: Experimental frequency map plotted together with information about the fractional beam loss.

Indeed, during the measurement we recorded significant beam loss (Fig. 4) at this intersection (and above, since particles launched to higher amplitudes cross through that intersection due to radiation damping) quite in contrast to the first experiment, where the beam was kicked to the same amplitudes but no significant beam loss was recorded.

5 CONCLUSIONS

The frequency map measurements at the ALS show the full network of coupling resonances in a Hamiltonian dynamical system of 3 degrees of freedom. The comparison of predicted and measured frequency maps shows that the (relatively simple) calibrated machine model using nominal sextupole strengths and measured gradient and coupling errors describes the nonlinear dynamics in the ALS remarkably well. Because of the good agreement we are now using the calibrated machine model and simulated frequency maps as a routine tool to predict the impact and to optimize future modifications of the ALS lattice. In addition the model independent diagnostic capability of experimental frequency maps was demonstrated and the interpretation of frequency maps was cross calibrated by comparing measured beam loss information with the resonance structure.

6 ACKNOWLEDGMENTS

This work was partly funded by the France-Berkeley Fund, CNRS, and CEA. The authors thank the staff at the Advanced Light Source and particularly Alan Jackson and Ben Feinberg for their encouragement and support for this work and Winnie Decking for helpful discussions and suggestions.

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