QUANTITATIVE LATTICE OPTIMIZATION USING FREQUENCY MAP ANALYSIS*

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Abstract

Frequency Map Analysis has been used successfully to study accelerator lattices for many years, both in simulations and in experiment. We will present a new application to use the quantitative results of frequency maps—namely the diffusion rates—to optimize the nonlinear properties of lattices. The technique is fairly simple but powerful and has already been used to optimize lattices for example for the NLC and ILC damping rings, as well as the ALS lattice upgrade.

INTRODUCTION

Frequency map analysis [1] has been in use for particle accelerators for well over 10 years now. It started as a tool to understand the global dynamics of the system, usually mapping $x - y$ configuration space into ν_x, ν_y tune space. Later is was expanded to be used on measured data [2], as well as to study off energy dynamics [3]. Fig. 1 shows an example of a simulated frequency map for the ALS in tune space (top) as well as configuration space (bottom). The simulation was carried out including (small) lattice errors, where the quadrupole and skew quadrupole gradient distributions were derived from measured orbit response matrix analysis. The color code indicates the tune diffusion rate, defined by

$$d = \sqrt{(\nu_{x,1} - \nu_{x,2})^2 + (\nu_{y,1} - \nu_{y,2})^2}/N \qquad (1)$$

on a logarithmic scale, where $\nu_{x,1}$ denotes the horizontal tune calculated for the first N turns of tracking data, $\nu_{x,2}$ the one for the following N turns.

Further simulation studies as well as detailed experiments over the years provided the experience to identify, which resonance structures in frequency maps tend to be dangerous, when adding for example additional machine errors, or insertion devices, and which ones are not. One very simple rule of thumb turned out to be, that if it is possible to minimize any areas with high diffusion rate within the region of interest, which could be the area in $x - y$ configuration space required for injection, or the area in $x - \Delta p/p$ space required for sufficient Touschek lifetime, those lattices have excellent dynamic properties and are usually fairly robust against additional errors. So using appropriate scanning or optimization techniques to find these lattices appeared like a desirable approach to nonlinear lattice optimization. It is an integrated numerical approach which is capable of delivering global minima, whithout necessarily revealing why the final solutions are optimal. However, we believe that the integrated nature of the optimization is a strength of the method, since the method basically balances itself between just to name one example minimizing detuning with amplitude versus minimizing resonance strengths without requiring the decision of an experienced user. The optimum solution found with such an integrated method will in general be very different than if one optimizes lattices by systematically looking at individual terms, like detuning with amplitude and low order resonance driving terms.

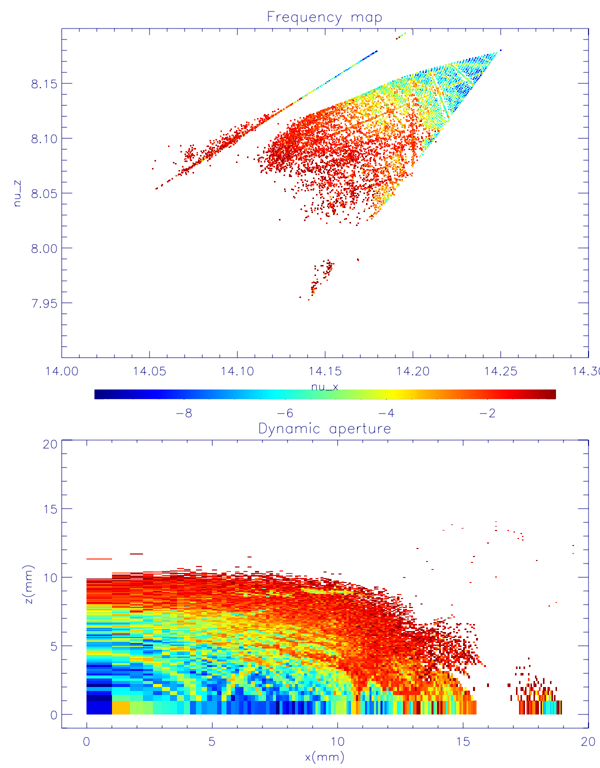

Figure 1: Simulated Frequency Map for the ALS lattice with errors in configuration and frequency space.

USE OF DIFFUSION RATES AS OPTIMIZATION GOAL

At the ALS, for about 5 years frequency map diffusion rates have been used to quantitatively compare different lattices and to optimize nonlinear lattices. Parameters that were used in the optimization included settings of sextupoles and harmonic sextupoles, fractional tunes, insertion device compensation schemes, etc. In order to come up with a quantitative number describing the 'quality' of a

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lattice, we start by defining regions of interest in $x - y$ or $x - \Delta p/p$ configuration space.

Choices in Calculation of Diffusion Rates

In $x - y$ configuration space, the main consideration is dynamic aperture and injection efficiency. For the ALS, the beam is injected with an offset of about 8 mm and the horizontal beamsize of the beam from the booster synchrotron is over 1 mm. Vertically we want to make full use of the physical aperture inside our small gap or in-vacuum insertion devices, again to maximimze injection efficiency and elastic gas scattering beam lifetime. So we usually use a configuration space of 10 mm horizontally and 2.5-3.5 mm vertically at the injection point, depending on whether we simulate the case with the in-vacuum undulator closed or open.

In the case of looking at the $x - \Delta p/p$ confiduration space, the main consideration is dynamic momentum aperture and Touschek lifetime. The bucket acceptance of the ALS rf system at 1.9 GeV is between 2.5 and a little over 3 %, depending on the momentum compaction factor. The size of the desirable horizontal is determined by the abovementioned rf-bucket acceptance and the H-function at the location of Touschels cattering effects. For typical lattices we study at the ALS, this results in horizontal apertures of 10-15 mm.

Once one has determined the area of interest over which to calculate the quality factor, in our case the sum of the diffusion rates, one has to consider a few more choices. The first one is the number of turns in the simulation. Because of the very fast (N^4) convergence of the NAFF algorithm used in the tune calculation, it is usually sufficient to just track for 100-200 turns. The next choice is the spacing and shape of the grid on which to calculate. We have found that it is sufficient to use about 10×10 intial conditions. In terms of spacing, we use a grid equidistantly spaced in betatron amplitudes. This tends to emphasize stability at large amplitudes, which allows good differentiation between similar lattices, while still avoiding selection of lattices with abnormal diffusion behavior at small amplitudes. The last choice one has to make in the algorithm is how to treat particles that are lost during the number of turns selected for the tracking. We found that assigning them a fictitious but fixed diffusion rate, i.e. the same number for every particle lost, and choosing one just a little larger than the largest diffusion rates we normally observe for surviving particles, was a good approach.

Results for ALS Upgrade

The ALS low emittance/sextupole upgrade is the latest in a series of upgrades and was started 2009. When it will be completed, the ALS will operate with a horizontal emittance of 2.2 nm and an effective emittance of 2.6 nm, roughly a factor of three reduction from the current horizontal emittances. This is achieved by increasing the phase advance per cell and the dispersion in the straight sections. The upgrade requires the addition of harmonic sextupoles to allow sufficient dynamic (momentum) aperture and to keep the strength of the exiting sextupoles within physical limits [4].

The technique described above was used to optimize the nonlinear behavior in the candidate lattices found by other techniques. For the baseline lattice chosen for the upgrade project, it was sufficient to just find the optimum settings for (in the simplest case) two families of harmonic sextupoles, while keeping the chromaticity and tunes fixed. The tracking was done both in $x-y$ and $x-\Delta p/p$ configuration space to optimize injection efficiency and Touschek lifetime. Tracking was carried out using AT including lattice errors and physical apertures (for a few, fixed error seeds). Fig. 2 shows the result of the scan of the two harmonic sextupole families, while keeping the chromaticities fixed (by adjusting the chromatic sextupoles). The vertical scale is the sum of all diffusion rates, summed over the region of interest in configuration space as described above. The scan shown did take about one hour of computation time on a single desktop computer. There is a clear optimal region, visible as a deep valley, but looking closer at the details, there are still significant differences also visible in small differences in the diffusion rates between the solutions within that valley.

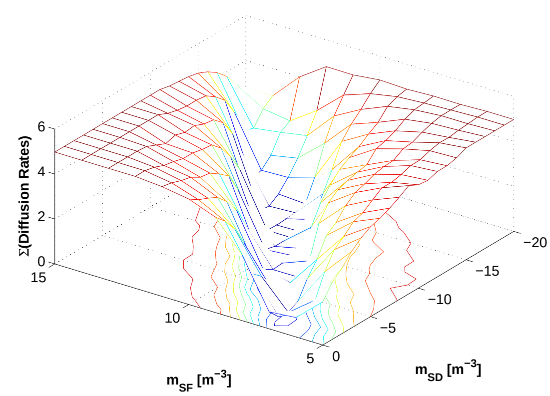

Figure 2: Example of two dimensional parameter scan (harmonic sextupole strength) and resulting sum of frequency map diffusion rates.

After finding an optimum solution, it can be investigated further. Fig. 3 shows an on-energy frequency map for the optimzied baseline lattice of the upgrade, including lattice errors and physical apertures. We found that the optimum solution arrived at with this technqiue tended to be very stable when adding further lattice errors, or effects of the intrinsic nonlinearities of the insertion devices, which in the case of the Eliptically Polarizing Undulators can be large. The dynamic aperture is more than sufficient for injection and in fact larger than for the present ALS lattice.

Similar results were simultaneously achieved regarding the dynamic momentum aperture and again the optimized solution of the upgrade lattice has a larger momentum aper-

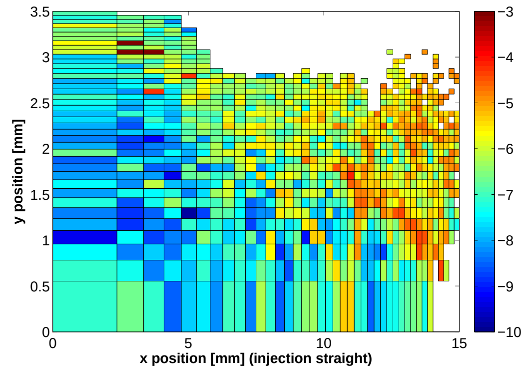

Figure 3: Example of an optimized frequency map for the baseline lattice (including magnet errors and physical apertures)

ture and larger predicted Touschek lifetime than the current ALS lattice, despite the smaller emittance.

ILC Damping Rings

Our method was also applied by other groups for optimization of ILC damping ring lattices. One example can be found in [5]. Like in the ALS case shown above, simple grid scan techniques were used for small numbers of simultaneously varied parameters. The studies helped to find lattice versions which performed substantially better in full tracking simulations than the starting versions before using the diffusion optimization technique.

APPROACHES FOR MANY OPTIMIZATION PARAMETERS

The latest light source designs usually employ around 10 quadrupole and 10 sextupole families or individual magnet control with reduced symmetry due to requirements of individual beamlines or lattice insertions. In those cases, simple scanning techniques like the ones describe above are not capable of finding optimum solutions because of the prohibitive computation times. In recent years, multiobjective genetic algorithms have found their way into accelerator applications. Using genetic algorithms computation times using the diffusion optimization technqiue described above even for 10-20 parameters remain within the limits of common parallel computer clusters providing a good possibility of finding global optima. In Berkeley, we started to work on including the frequency map diffusion rate calculations into our previous genetic algorithm work which had centered on linear lattice design [6].

Many other approaches are in use to find optimum nonlinear solutions for complex light source lattices. One common approach is to systematically attack low order resonance driving and detuning terms [7]. A second approach is to apply brute force tracking of a large number of particles and directly calculating injection efficiency and beam lifetime from the tracking, using those results in a genetic optimization algorithm [8]. The first approach is possible with relatively little computational effort, but requires a lot of user expertise and in many cases might only find local optimal solutions. The second approach is very good at finding robust and globally optimal solutions, but is very computationally intensive. We believe our approach falls somewhat in the middle. It provides a little more insight into why solutions are good and bad, if one looks at some of the frequency maps, and does not require tracking of nearly as many particles for as many turns as the second approach. It usually is better than the first approach in finding global optima. However, in practical situations, the differences might not be significant.

SUMMARY

Frequency map analysis has been a very powerful tool to understand and improve the nonlinear dynamics behavior in particle accelerators. We have used a technique to make use of the quantitative diffusion rates from frequency map analysis to compare the performance of different lattices and to carry out an automated lattice optimization. The results have been very good in multiple applications and the lattices optimized this way are for example the baseline for the ALS low emittance upgrade.

REFERENCES

[1] Dumas, H. S., Laskar, J., Global Dynamics and Long-Time Stability in Hamiltonian Systems via Numerical Frequency Analysis, Phys. Rev. Lett. 70 2975–2979

[2] D. Robin, C. Steier, J. Laskar, L. Nadolski, Global Dynamics of the Advanced Light Source Revealed through Experimental Frequency Map Analysis, Phys. Rev. Lett. 85, 3, (July 2000), pp. 558-561

[3] C. Steier, et al., Measuring and Optimizing the Momentum Aperture in a Particle Accelerator, Phys. Rev. E 65:056506, 2002

[4] C. Steier, Low Emittance Upgrade of the ALS, These Proceeedings

[5] I. Reichel, Frequency Map Studies for the ILC Damping Rings, Proceddings of PAC 2007, Albuquerque, NM, USA, p. 2987

[6] L. Yang et. al, Nucl. Instr. & Meth. A 609 (2009) 50-57

[7] J. Bengtsson, SLS Note 9/97 (1997).

[8] M. Borland, et al., Proceedings of PAC 2009, Vancouver, BC (2009).