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D. Robin and J. Laskar
**Accelerator and Fusion
Research Division**

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UNDERSTANDING THE NONLINEAR BEAM DYNAMICS OF THE ADVANCED LIGHT SOURCE

David Robin

Advanced Light Source
Accelerator and Fusion Research Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

Jacques Laskar

CNRS, Astronomic et Systemes Dynamiques
Bureau des Longitudes 3
rue Mazarine
75006 Paris

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David Robin

*Lawrence Berkeley National Laboratory
Berkeley, CA 94720 ; e-mail: robin@lbl.gov*

Jacques Laskar

*CNRS, Astronomie et Systèmes Dynamiques, Bureau des Longitudes
3, rue Mazarine, 75006 Paris ; e-mail: laskar@bdl.fr*

Abstract. Frequency map analysis is used to study the single particle transverse beam dynamics in the Advanced Light Source. The maps, which provide details about the diffusion of orbits and limits on long term stability, are generated by a postprocessor attached to a tracking code. In this paper we describe the method and show how the map is changed when the 12-fold symmetry of the linear lattice is perturbed by including measured magnetic field imperfections. Also the long term stability of orbits that reside in regions of large diffusion is studied.

INTRODUCTION

In a particle storage ring, the stability of the particle motion affects both the beam lifetime and the injection efficiency. If the motion of particles at large amplitudes is unstable, then particles which are scattered to large amplitudes via gas or intrabeam scattering may become lost. If the motion of particles is chaotic, then particles may also become lost due to orbit diffusion. Similarly, particles injected at large amplitude may not survive. So for long beam lifetimes and good injection efficiencies it is necessary to design and operate rings which have large stable phase space areas.

Typically, ring designers rely heavily on short term tracking studies to determine the size of a ring's stable area. In these studies, a model of the ring exists in which particles can be tracked. Particles are launched in the model with a variety of different initial conditions and then tracked around the ring for a few hundred to a few thousand terms or until the particles become lost. The short term dynamic aperture is then drawn as a boundary that separates the region of space where particles survived from the region where they were lost. The short term dynamic aperture is then judged to be sufficiently large based on certain criteria which are necessary for long beam lifetimes and high injection efficiencies. If the short term dynamic aperture is not large enough, then the lattice design needs to be modified.

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Short term dynamic aperture studies by themselves provide minimal information about the beam dynamics. The results of these studies only specify whether a particle with a given initial condition will survive over a short time period. These studies provide no information about how unstable particles are lost, and thus about the long term stability of particles. As a result, short term dynamic aperture studies are of limited help for improving the design of the lattice.

Frequency map analysis is a numerical method that is useful in studying the stability of dynamical systems. Frequency map analysis was developed by Jacques Laskar (1-6) who initially applied the method towards problems in celestial mechanics. According to the KAM theorem (7-9), in the phase space that is sufficiently close to integrable conservative system, many invariant tori will persist. Trajectories starting on one of these tori remain on it thereafter, executing quasiperiodic motion with a fixed frequency vector depending only on the torus. The frequency analysis method will numerically compute the frequency vectors associated with each of these invariant tori.

Although the frequencies are strictly speaking only defined and fixed on these tori, the frequency analysis algorithm (NAFF) will numerically compute over a finite time span a frequency vector for any initial condition. One can thus construct a map, called the frequency map, which will associate the frequency vector to each set of action-like initial conditions. On the set of initial conditions corresponding to KAM tori, the frequency vector will be a very accurate approximation of the actual frequencies, and the frequency map will be smooth as the restriction to this set of a true diffeomorphism (11), which will not be the case in the chaotic regions. Therefore one can then distinguish between regular and nonregular orbits by just looking to the frequency map. Moreover, the frequency vector of regular orbits will remain fixed within numerical accuracy. Those that do not remain fixed are also revealed as nonregular and their orbits are chaotically diffusing.

The NAFF algorithm is described in detail in other papers (2,4,11). The focus of this paper is to study the dynamics of the Advanced Light Source (ALS) storage ring lattice using frequency map analysis. In the paper, the procedure to generate the frequency map is outlined. First the map of the ideal lattice (no errors) is presented. Second, measured linear focusing errors are included in the lattice which shows enhanced resonance excitation and its effects on the injection rate. Finally the results of long term tracking studies are presented.

GENERATING FREQUENCY MAPS

Two ingredients are necessary in order to generate the frequency map. The first is a model of the lattice in which a particle can be tracked, turn-by-turn, around the ring. The second is a frequency analysis postprocessor which takes the turn-by-turn tracking data and computes the fundamental frequencies (NAFF package).

For the study of the ALS, a new computer code is written that combines a particle tracking code, DESPOT (14), with the NAFF postprocessor. Particles are launched on a regular mesh in action space. (In all cases presented in this paper, the particles were launched with an initial position offset but no initial angle.) Each particle is then tracked for N turns ($N = 1024$ for the results in this paper) or until the particle is lost. Each surviving particle is mapped into the frequency plane by computing the fundamental frequencies or tunes of that particle by means of frequency analysis. For each run, 40,000 particles (400×100 mesh) are tracked.

In the case of the ALS, more than 99% of the computational time is spent in the tracking loop. There is little overhead in the computation of the frequencies.

The particles are tracked in series. On a dedicated SUN SPARC 10 workstation the map takes several days to generate. However, since all the particles are completely independent of each other, the particles could in practice be tracked in parallel. Therefore the generation of the frequency map is ideally suited to run on a massively parallel processing (MPP) machine where the map would take minutes instead of days to generate.

ADVANCED LIGHT SOURCE

Dumas and Laskar first applied frequency map analysis techniques in accelerator dynamics to the study of the global dynamics and diffusion of a modeled cell of the ALS (1). Later Laskar and Robin studied the full 12-cell ALS lattice and looked at the effect of artificial symmetry breaking (15). In that study one quadrupole was detuned by 5%. The detuned lattice showed strong excitation of low-order resonances that were not excited in the ideal ring. This increase in resonance activity caused a reduction in the dynamic aperture. An inspection of the map clearly showed that the nominal working point was not the optimal one in order to maximize the size dynamic aperture. By just looking at the map it was possible to predict the position of a better working point where the map is cleaner and the dynamic aperture is larger.

In this paper frequency maps are generated for lattices with measured gradient errors. Also the issue of long term stability is explored through long term tracking of certain particles that lie in chaotic regions of the map. In all cases presented in this paper, particles are tracked on-energy and with no synchrotron oscillations.

In Figure 1, the results of short term tracking of the ideal lattice is presented. Each of the points plotted in Figure 1 (left plot) represent the initial coordinates of all particles that survived 1024 turns. As can be seen from Figure 1, the dynamic aperture extends to more than 22 mm horizontally and 11 mm vertically at the tracking point.

Ideal Ring

FIG. 1. Ideal lattice: Initial coordinates of all particles that survived 1024 turns (left) and the corresponding frequency map in frequency space (right).

The frequency map is generated by computing the tunes of each surviving particle (using the first 1024 turns) and mapping them into the frequency plane. The frequency map for the ideal lattice is presented in Figure 1 (right plot). The working point of the machine is $\nu_x = 14.28$ and $\nu_y = 8.18$ (upper right corner of Figure 2).

Small amplitude particles tend to oscillate with tunes close to the working point. Particles with large amplitudes oscillate with tunes that are shifted left and downward from the working point. This is due to the negative tune-shift with amplitude that is generated by the sextupoles. In particular, particles that are oscillating at large horizontal amplitudes are shifted more downwards, and particles that are oscillating at large vertical amplitudes are shifted more to the left.

We also see the influence of resonances in the map. In regions of tunespace where there are no strongly excited resonances, the tunes are evenly spaced. In regions of the map where there are strongly excited resonances the tunes are unevenly spaced. In these regions the motion may be chaotic and the particles may have large orbit diffusion rates.

Lattice with Measured Errors

The ALS lattice is designed with 12 sectors which in the ideal ring are all identical (12). The beam dynamics in the ALS lattice is very sensitive to linear focusing errors which perturb the natural 12-fold symmetry of the ring. When the symmetry of the lattice is broken, many low-order resonances, that were previously not excited in the ideal ring, may become excited. This increased resonance excitation has been observed experimentally in the beam tail distributions (13). As a result gradient errors coming from mispowered quadrupoles or orbit misteering in sextupoles can greatly effect the dynamic aperture and beam profile.

Because of this fact, in the spring of 1996, the gradient distribution of the ring was measured (16). The measurements revealed that four quadrupoles were more than 1% lower than the rest. The errors created an rms perturbation of the betatron function that is as large as 6% horizontally and 19% vertically. These measured gradient errors were included in the lattice and the map was generated. The resultant map can be seen in Figure 2 (left plot).

FIG. 2. Frequency map with measured errors (left) and with symmetry partially restored (right)

Comparing the frequency map for the ideal ring (Figure 1) with this map it is clear that the dynamic aperture is smaller in the ring with broken symmetry. Also there is an enhancement of low-order resonance excitation. In particular, one sees that many excited resonances intersect in the region near the tune of 14.25 horizontally and 8.125 vertically. This is a critical area because this is close to where particles are injected into the ring (see Figure 2). Because of the enhanced resonance excitation, one might imagine that as particles are injected into the ring, they may chaotically diffuse out of the beam. In other words, this increase in resonance activity may

have an impact on our injection efficiency.

The ring's symmetry was partially restored by adjusting individual quadrupole gradients in the lattice. The model was then refit to match the new ring. The resulting betatron beating was measured and found to be less than 1% both horizontally and vertically (16). A map for this new lattice was generated and the results can be seen in Figure 2 (right plot). Comparing the left and right plots in Figure 3, it is clear that the more symmetrical lattice has a much cleaner map than the old lattice. As a result one would expect that the injection rates would be better in that lattice. A measurement of the injection efficiency was made for the two lattices. The injection efficiency was found to be a factor of two larger in the more symmetrical lattice (16).

Orbit Diffusion

In a previous paper (3), Laskar used frequency map analysis to study the diffusion of orbits in the case of a four dimensional symplectic map. In that study, orbits were followed over an extended time with the frequencies being calculated at regular intervals. This allowed their orbits to be tracked in the frequency plane. As expected, in regular regions of the map there was practically no diffusion. In nonregular regions of the map the diffusion rate was very rapid and some particles escaped. A similar study is made here for the ALS system. It is shown that the map provides an intuitive understanding of the long term stability of the particles.

FIG. 3. Orbit diffusion of four orbits over 500,000 turns

In particular, let's look at diffusion in the lattice in the case of large symmetry breaking (left plot in Figure 2). In Figure 3 the background points are just the same as the points plotted Figure 2. Several distinct orbits (O_1 , O_2 , O_3 and O_4) are followed over an extended time (500,000 turns). On each interval of 1024 turns the frequencies are computed and plotted as points connected by lines. For the orbit, O_1 , in a regular region, there is practically no diffusion. For orbits in nonregular regions (O_2 , O_3 and O_4) the diffusion is large. Take the orbit O_2 for example. The diffusion is large but perpendicular to the $3\nu_x + 2\nu_y = 59$ resonance. However the diffusion of the orbit is bounded by regular regions of the map that border that resonance. Because of the direction of the diffusion and the location of the regular regions, it is unlikely that particles in the region will escape in a reasonable time.

On the contrary, orbits O_3 and O_4 escape in a relatively short number of turns ($< 100,000$). Unlike the diffusion of the orbit O_2 , the related nonregular region of the frequency map is not bounded, but widely open on the outside of the beam. Thus many resonances overlap, and the direction of the diffusion for both O_3 and O_4 randomly changes. Therefore one suspects that many particles in this nonregular area will escape.

SUMMARY

This study demonstrates how frequency map analysis uncovers the global dynamics of the ALS. The method clearly shows how resonance excitation increases and the injection efficiency suffers when measured errors are included in the model. The method also provides strong intuition about orbit diffusion and particles long term stability.

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