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In collaboration with visiting scientists from the Astronomie et Systèmes Dynamiques department at the French Bureau des Longitudes in Paris, accelerator physicists from the Advanced Light Source (ALS) at the Ernest Orlando Berkeley National Laboratory (Berkeley Lab) have applied the technique of frequency map analysis to experimental measurements of the electron beam in the ALS. Owing to the high quality of the measured frequency map, they could distinguish between regions of phase space where the motion was regular or chaotic, thereby observing the network of resonances in the frequency map for the actual storage ring. The excellent agreement between the map based on experimental data and that obtained with calibrated numerical models leads the scientists to propose the use of the technique as a tool to improve both numerical models and the behavior of actual storage rings, including parameters important to synchrotron radiation users such as lifetime and injection efficiency.

In a storage ring, the focusing fields of the quadrupole magnets cause electrons to oscillate transversely about the closed, central trajectory that represents the ideal orbit. The number of oscillations in one turn around the ring is called the betatron tune and can be different in the horizontal and vertical directions. In addition, the oscillations are nonlinear and the oscillation frequencies change with the transverse amplitude of the electrons. Since the tunes depend on the fields produced by the magnets in the storage-ring lattice, accelerator operators can adjust them to some extent.

The motion of electrons with large transverse amplitudes may be influenced by resonances. If resonances are strongly excited, they decrease the stability of the electron beam by causing irregular, chaotic electron behavior, leading to loss of electrons as they diffuse to the outer, unstable region of the beam. For example, resonances can prevent electrons injected into the storage ring at large amplitudes from being accumulated, thereby lowering the injection efficiency, or stored electrons initially circulating in stable orbits can be scattered by collisions with residual gas molecules or other electrons to unstable orbits, where they are lost, thereby lowering the beam lifetime.

Resonances can be excited when the horizontal and vertical betatron tunes (ν_h and ν_v) satisfy the relation $N_h\nu_h + N_v\nu_v = R$, where N_h, N_v, and R are integers. For the ideal ALS storage ring with twelve-fold periodicity, the resonance condition is more restrictive; the integer R must be a multiple of 12. For a real storage ring with magnetic imperfection it is very difficult to calculate the actual strength of a resonance. Therefore as a rule of thumb, one tries to avoid resonances of low order ($|N_h|+|N_v|$), which tend to be large. In addition one can make empirical adjustments of the tunes to improve the machine performance. This process is time consuming and may not lead to the optimum solution. Therefore a reliable, accurate method of finding which resonances actually are excited would be welcome.

About 10 years ago, Jacques Laskar, an astronomer at the Bureau des Longitudes, developed the technique of frequency map analysis to study the global dynamics of multidimensional systems. In numerical simulations of physical systems ranging from galaxies to particle accelerators, it has proven very effective, particularly for systems with three or more degrees of freedom. Stripped to the basics, the main steps of the analysis are selection of initial coordinates (e.g., position and momentum), numerical integration of the equations of motion, a fast converging modified Fourier technique (NAFF) to obtain a quasi-periodic approximation to the calculated trajectories, and extraction of the fundamental frequencies. In the case of a storage ring, the fundamental frequencies correspond to the tunes.

Using these tools, the amplitude of the transverse particle motion is mapped into frequency space associating a pair of fundamental frequencies with the transverse amplitudes. This frequency map is displayed in a coordinate system with the horizontal and vertical tunes as the axes. From the nominal working point corresponding to small transverse amplitude oscillations, the frequencies shift over a wide area as the amplitudes of the betatron oscillations increase. Damaging resonances show up as distortions in the map and appear as lines, as given by the resonance equation. Accelerator physicists at the ALS have used frequency map analysis for several years with numerically generated data from a model. In these simulations the frequency maps turned out to be very sensitive to the distribution of magnetic-field errors in the model. Even for a machine with very small field errors, there is a striking difference in the frequency map as compared to the ideal machine, with smaller stable areas and larger chaotic regions resulting from the errors.

With an eye towards revealing the true dynamics of the particle beam, the ALS accelerator physicists wanted to construct an experimental frequency map based on measured beam oscillations. The ALS is equipped with two tools that provide the required data. First, a set of two "pinger" magnets whose fields rise and fall in a time less than it takes the electrons to travel around the ring can deliver horizontal and vertical kicks, respectively, to the beam, thereby displacing the beam with independently adjustable horizontal and vertical amplitudes. Second, beam-position monitors synchronized with the pinger magnets can measure the transverse center of charge of the electron beam for each turn around the storage ring. The beam-position monitors can store data for up to 1024 turns.

In their first experiment, the researchers (David Robin and Christoph Steier from the ALS and Jacques Laskar and Laurent Nadolski from the Bureau des Longitudes) collected data for a set of 25 × 25 initial transverse momenta. They set the small-amplitude betatron tunes at $\nu_h = 14.25$ and $\nu_v = 8.18$ (close to the setting for user operation), and adjusted magnet parameters so that the storage ring was as close as possible to 12-fold periodic. Under these conditions, they found the frequency map contained two strongly excited coupling resonances of fifth order ($|N_h| + |N_v| = 5$). These resonances are particularly interesting because they are "unallowed" (R is not a multiple of 12) and do not appear in the frequency map for the numerical model of the ideal, 12-fold symmetric storage ring, whereas they do show up in the frequency map calculated using a machine model with realistic errors. It appears that small coupling errors in the storage-ring lattice broke the 12-fold periodicity sufficiently to excite the unallowed resonances.

In a second experiment, the working point was changed to an older setting that had been associated with an erratic injection efficiency. The frequency map based on experimental data showed three strongly excited resonances intersecting at a common point, a particularly dangerous condition owing to induction of rapid diffusion of electrons out of stable trajectories. In fact, such beam loss actually was observed during the experiment.

One limitation of frequency map analysis at present is the rather long time it takes to gather the data, about 4 hours for 600 initial conditions, which makes it impractical for on-line monitoring of the beam quality. The researchers believe that it will be possible to reduce the data-acquisition time considerably and look forward to using frequency map analysis as a regular diagnostic tool for optimizing the performance of the ALS.

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References

1. D. Robin, C. Steier, J. Laskar, and L. Nadolski, *Phys. Rev. Lett.* **85**, 558 (2000).

Figure Captions: [no electronic images available]

[Figure 1]
Frequency maps for the ideal lattice of the ALS (upper left) and for a lattice including measured gradient and coupling errors (upper right) from orbit-response matrices. Blue areas represent electron trajectories with no diffusion (no change in betatron tune), and red areas represent particles with high rates of diffusion. Note that the color scale is logarithmic, so that the diffusion rate for electrons in the red regions is about one billion times that of electrons in the blue regions. The lower plots show the frequency map in configuration space (i.e., the transverse displacement of each electron from the closed orbit at the injection point).

[Figure 2]

Comparison of a measured frequency map of the ALS (a) with a simulated one based on gradient and coupling errors measured from the orbit-response matrices (b). Resonances of order ≤5 are shown as dotted lines.

[Figure 3].]

Experimental frequency map for an older setting of the ALS storage ring tunes showing an intersection of three strongly excited resonances.