Frequency Map Analysis Applied to the ALS

A Mathematical Technique to Improve Storage-Ring Performance

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) have applied the technique of frequency map analysis to measurements of the electron beam in the ALS. 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 to improve both numerical models and the behavior of storage rings, including important parameters 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. Tunes can be different in the horizontal and vertical directions, and they change with the transverse amplitude of the electrons. The motion of electrons oscillating with large transverse amplitudes is subject to resonances that can decrease the stability of the electron beam, resulting in loss of electrons, which affects operation for synchrotron radiation users because it increases the time it takes to store a beam and decreases the time the beam subsequently remains in the storage ring.

For a real storage ring with magnetic imperfections it is very difficult to calculate the actual strength of a resonance. 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. The calculation of the frequency maps involves numerical integration of the equations of motion with a fast converging modified Fourier technique to obtain a quasi-periodic approximation to the calculated trajectories from which the fundamental frequencies are extracted. In the case of a storage ring, the fundamental frequencies correspond to the tunes. Later Laskar working together with accelerator physicists from the ALS showed that numerically calculated frequency maps were very sensitive to the distribution of magnetic-field errors in the model, with smaller stable areas and larger chaotic regions resulting from even minor errors.

With an eye towards revealing the true dynamics of the electron beam, the ALS accelerator physicists wanted to construct a 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 can displace 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.

In their first experiment, the French-American team collected data for the ALS at the condition for normal user operation. The resulting frequency map contained two strongly excited resonances that were particularly interesting because they were "unallowed" and did not appear in the frequency map for the numerical model of the ideal, 12-fold symmetric ALS storage ring. It appears that small coupling errors in the storage-ring lattice broke the 12-fold periodicity sufficiently to excite the unallowed resonances, in excellent agreement with numerical models that include realistic errors. Since these are isolated resonances bound by stable regions, they were not harmful.

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 was observed during the experiment. ■

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D. Robin, C. Steier, J. Laskar, and L. Nadolski, "Global Dynamics of the Advanced Light Source Revealed through Experimental Frequency Map Analysis," *Phys. Rev. Lett.* **85**, 558 (2000).

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FREQUENCY MAP ANALYSIS APPLIED TO THE ALS

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- **Resonances decrease storage-ring performance**
  - *Large-amplitude electrons less stable*
  - *Lowered injection efficiency*
  - *Reduced beam lifetime*
  - *Difficult to calculate which resonances are harmful*
- **Frequency map analysis developed in France**
  - *Tool for global dynamics of multidimensional systems*
  - *Applied in past to numerical simulations of dynamic systems*
- **Experimental frequency map determination at the ALS**
  - *First map based on measurements of electron beam positions*
  - *Observe network of resonances*
  - *Determine which resonances most likely to cause beam instability*
  - *Agreement with frequency map for realistic storage-ring model*
- **Important diagnostic tool for optimizing performance**
  - *Simulate lattice modifications in numerical models*
  - *Improve behavior of actual storage rings*

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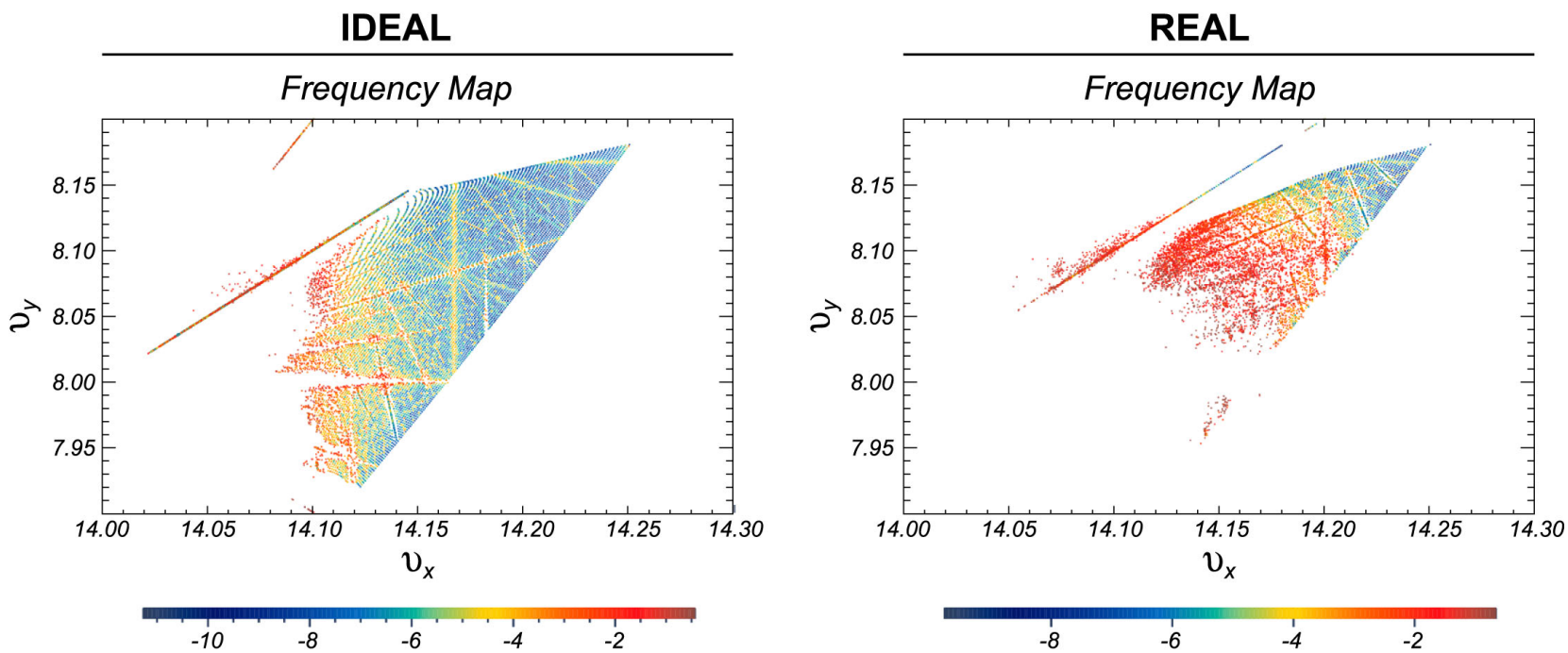

Simulated frequency maps for the ideal lattice of the ALS (upper left) and for a lattice including experimentally determined magnetic-field errors (upper right). In the logarithmic color scale, blue areas represent electron trajectories with no diffusion (no change in betatron tune), and red areas represent particles with high rates of diffusion.

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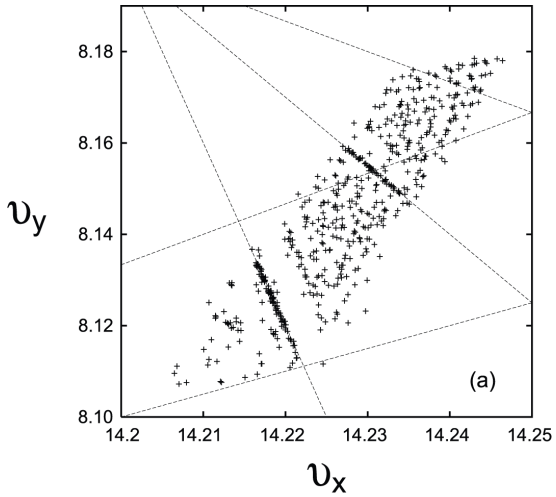
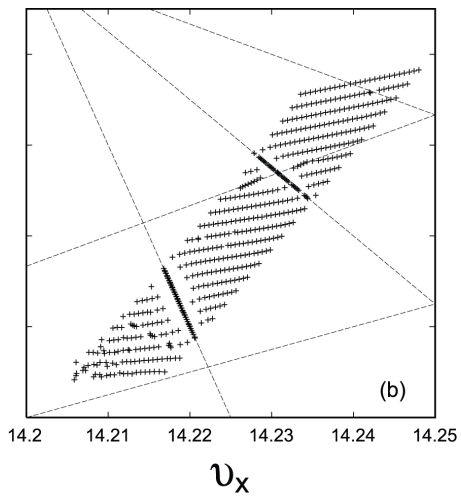
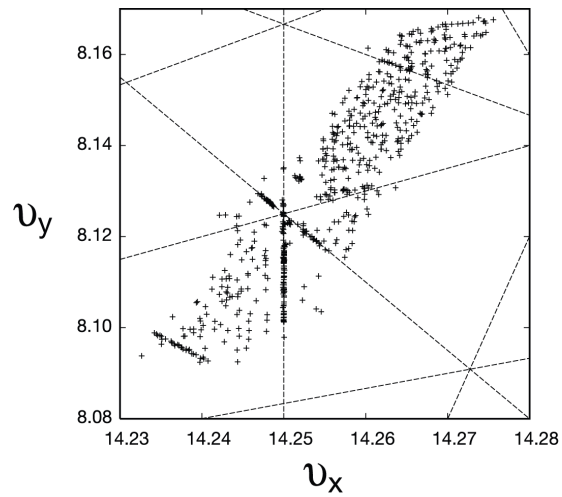


Measured frequency map of the ALS for the normal setting of the storage-ring tunes shows two strongly excited resonances (concentrations of points) that are not allowed in the ideal, 12-fold symmetric ring.



Simulated frequency map based on experimentally determined magnetic-field errors shows good agreement with the measured map, suggesting the errors break the 12-fold symmetry.



Experimental frequency map for an older setting of the ALS storage-ring tunes shows the intersection of three strongly excited resonances that can cause rapid diffusion of electrons out of stable trajectories.

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