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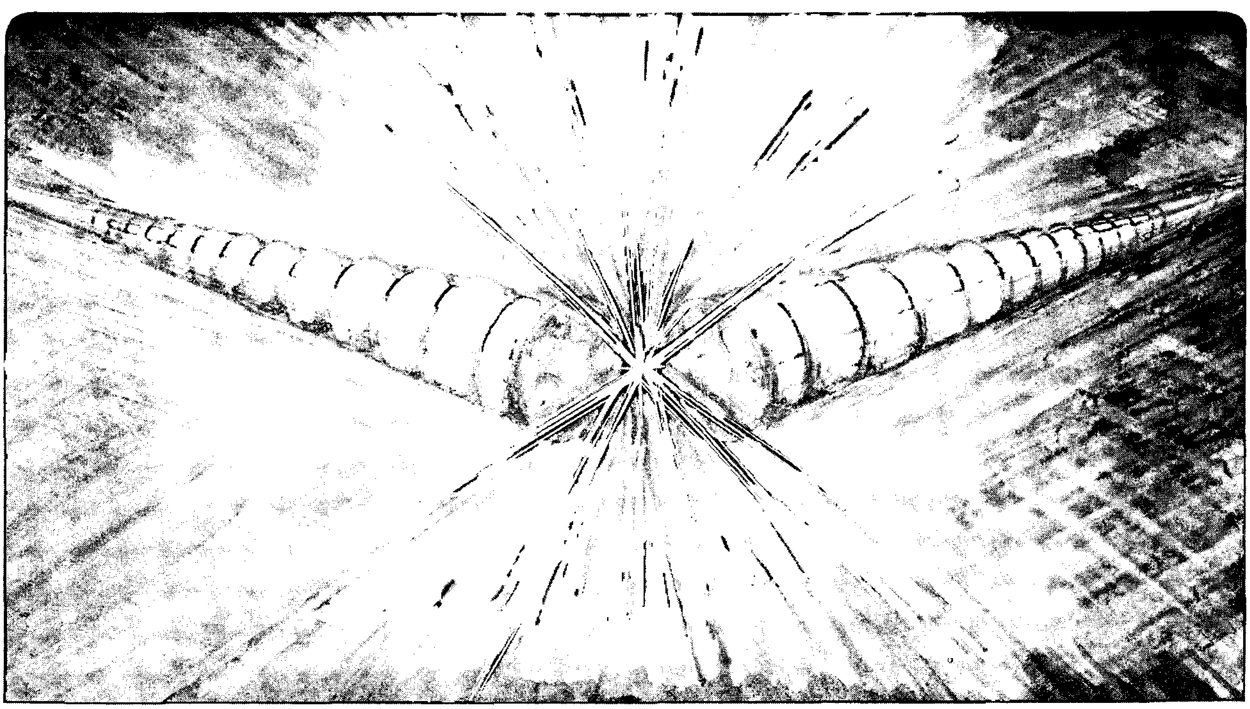

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Observation of Nonlinear Resonances in the Advanced Light Source[1]

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Abstract. Observations of nonlinear resonances in the Advanced Light Source have been made by scanning betatron tunes and observing count rates in a beam-loss radiation monitor placed down stream of a beam scraper. We have found that it is possible to see structural resonances which are unallowed as well as those which are allowed by the ring's natural 12-fold symmetry. By systematically breaking the amount of symmetry we see that the widths of the unallowed resonances grow while the widths of the allowed resonances do not. In this paper we briefly discuss the importance of symmetry and its effect on resonances in the design of the ALS. Next we describe our experimental setup and discuss the performance of the beam loss monitor which we used to view the resonances. We then present scans of the tune space where one can see the presence of the structural resonances and their evolution when the lattice symmetry is systematically broken.

INTRODUCTION

The Advanced Light Source (ALS) is one of the first members of a new family of synchrotron light sources called third generation light sources. These new light sources are designed to generate small beam emittances in order to enhance the brightness of the radiation emitted from undulators. The beam dynamics in these light sources are dominated by strong focussing magnets (quadrupoles and sextupoles) necessary to provide the small emittances. They need to be carefully designed to suppress nonlinear structural resonances otherwise these resonances can limit the performance and reliability of the machine by increasing the beam size and decreasing the beam lifetime.

In this spirit the lattices of all these light sources have been designed with a high degree of symmetry to minimize the effect of dangerous nonlinear structural resonances. The degree to which the symmetry of the lattices is broken, either by lattice imperfections or insertion devices, will effect how strongly resonances are excited and thus will influence how well the light sources will operate. The effect of symmetry breaking by insertion devices and compensation techniques in

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the ALS has been studied with particle tracking simulations (1) (2). Having a way of monitoring the onset of resonances allows us to observe the effect of symmetry breaking on the particle motion. It also gives us a way of measuring how well we can compensate for the symmetry breaking. This is the motivation behind our study.

Importance of Symmetry in the Design of a Lattice

If the horizontal, vertical and synchrotron tune of a particle in the storage ring is ν_x, ν_y, and ν_s respectively, resonances can be excited when the following condition is satisfied

$$N_x\nu_x + N_y\nu_y + N_s\nu_s = R \tag{1}$$

where N_x, N_y, N_s, and R are integers.

If the lattice is made up of an integer number, M, of identical pieces, the lattice is said to have an M-fold symmetry. For a lattice with an M-fold symmetry, equation 1 is modified to read

$$N_x\nu_x + N_y\nu_y + N_s\nu_s = M \times R. \tag{2}$$

The effect of symmetry is to reduce the number of resonances which can be excited. If M is large ($M = 12$ for the ALS) then the number of structural resonances that are suppressed is also large. So having a lattice with a high degree of symmetry is a very effective way of reducing the number of effective or allowable resonances thus improving the stablility of the beam motion.

OBSERVING STRUCTURAL RESONANCES

When excited, structural resonances may alter the behavior of particles in the beam's tail. Resonances may cause particles to increase and decrease their transverse amplitudes or to be trapped at large amplitudes. Therefore by monitoring changes in the beam tails as the betatron tunes are varied it is possible to observe the onset of resonances.

The way in which we monitor the tails is by limiting the transverse physical aperture with a beam scraper and measuring the beam lifetime (see next section) as a function of betatron tunes. If resonances are present in the vicinity of the tunes, more particles will hit the scraper when they make large amplitude excusions resulting in a shorter beam lifetime. If resonances are not present, fewer particles will hit the scraper resulting in a longer beam lifetime. Thus if we vary the betatron tunes while simultaneously observing the beam lifetime we will see the lifetime drop when we move onto excited resonances.

Experimental Method and Apparatus

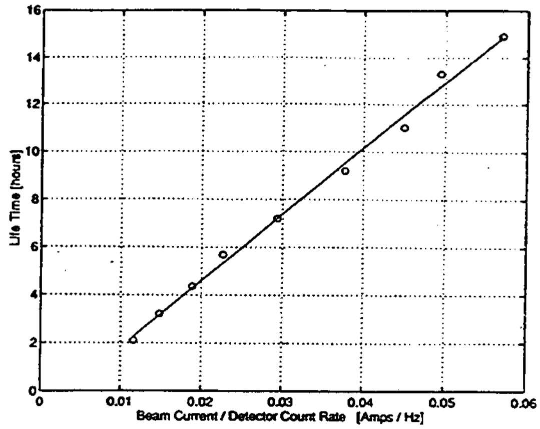

Figure 1. Relationship between the beam lifetime and the detector count rate.

The experimental technique is very similar to that which was used in VEPP-4 (3) to measure the effect of the beam-beam force on the tails of the beam. A beam loss monitor is located just down-stream of a horizontal scraper and the loss monitor detects gamma radiation being emitted from the scraper. The count rate detected is proportional to the rate at which particles hit the scaper and is related to the beam lifetime in the following way:

$$\text{Beam Lifetime } \alpha \; \frac{\text{Beam Current}}{\text{Detector Count Rate}} \; . \tag{3}$$

We measured beam lifetime verses beam current and beam count rate and found that equation 3 was valid in the region where we operated (see figure 1). Therefore by observing the change in the ratio of the beam current to the detector count rate as a function of betatron tune we can observe the onset of resonances.

Our experimental procedure was the following. We would first change the tunes by changing two families of quadrupoles according to a previously measured transfer matrix. After the quadrupole fields have settled we measured the beam current and the count rate in the detector for a 1 second interval. (The whole process is automated and takes about 2 seconds per tune.) In order to check how well our predicted tunes agree with the measured tunes we would periodically measure the tunes.

There are two advantages of measuring the count rate and current verses a direct measurement of the lifetime. First the measurement is fast. We can scan nearly 2000 tune values per hour. The second advantage is the fluctuation in our detector count rate is small (roughly 3%) which is due to the large detector count rate ($\sim$ 2 KHz for a 10 hour lifetime with a beam current of 100mA). The combination of a fast measurement and high sensitivity makes this technique more attractive than measuring the beam lifetime directly.

TUNE SCANS

We chose to scan in a region of tune space where two resonances are present: $5\nu_x = 72$ (allowed by symmetry) and $3\nu_x = 43$ (unallowed by symmetry).

The "Unperturbed" Machine

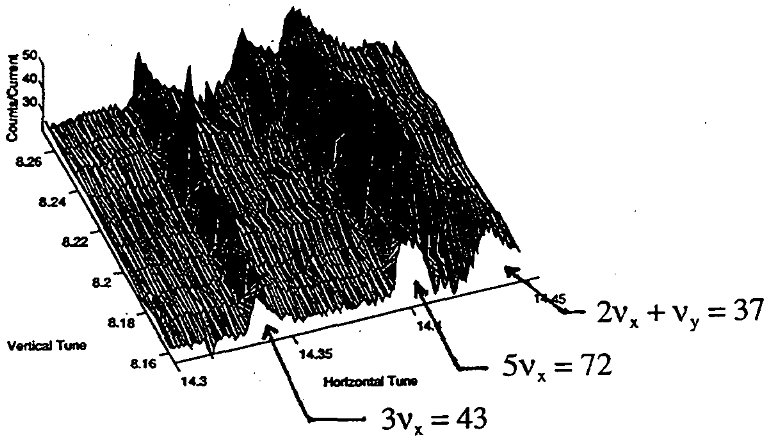

Figure 2. Tune scan of the "unperturbed" lattice. Peaks indicate the presence of resonances.

The first scan was made with the machine in its nominal state. The scan covered a rectangular region in tune space ($14.295 < \nu_x < 14.455$ and $8.155 < \nu_y < 8.270$). Within this region we scanned 150 horizontal tune values by 10 vertical tune values ($\Delta\nu_x$ steps of 0.001 by $\Delta\nu_y$ steps of 0.012).

All the quadrupoles in each family were set to the same current value and all of the insertion device gaps were open. Figure 2 shows the results of the scan. Three resonances can be seen in the scan:

$$5\nu_x = 72 \qquad \text{(allowed)}$$
$$3\nu_x = 43 \qquad \text{(unallowed)}$$
$$2\nu_x + \nu_y = 37 \qquad \text{(unallowed)}$$

Symmetry Breaking by Detuning 1 Quadrupole

Next we investigated the effect of symmetry breaking. We scanned horizontally ($\Delta\nu_x$ steps of 0.001) keeping the vertical tune constant ($\nu_y = 8.15$). In the scans we introduced some beta beating by detuning one quadrupole. The amount of beta beating introduced is proportional to the amount of quadrupole detuning. From our theoretical model of the machine we predicted the amount of beta beating introduced by the detuning (see table 1).

$\frac{\Delta I}{I}$	$\left(\frac{\Delta\beta_x}{\beta_x}\right)_{rms}$
0%	0%
1.33%	5.4%
2.67%	10.7%
4.00%	16.1%
5.33%	21.4%

Table 1. Relative quadrupole detuning verses induced horizontal beta beating

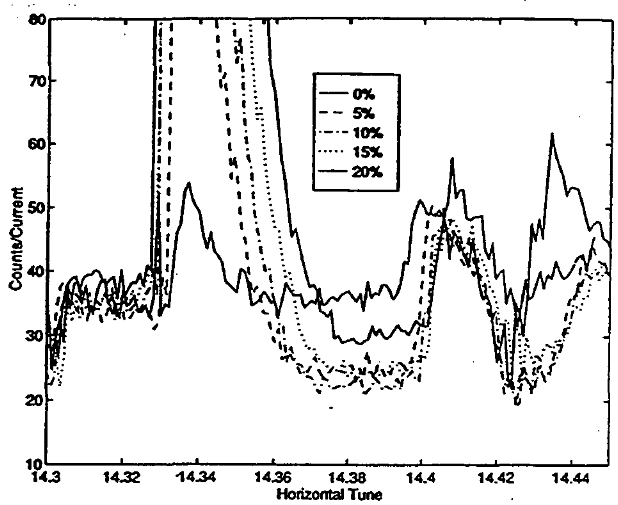

Figure 3. Horizontal tune scans ($\nu_y = 8.15$) for five different values of horizontal beta beating.

The results can be seen in figure 3. As we increase the relative detuning of the quadrupole, the width of the $3\nu_x = 43$ increases while that of the $5\nu_x = 72$ does not. In fact with just a 5% horizontal beta beating we lose the beam when we scan across the $3\nu_x = 43$ resonance.

Interpretation of the tune scan data

As mentioned earlier, the ideal, unperturbed machine allows only a few low order resonances to be excited within the scanned area. In fact the lowest order resonance present is a fifth order resonance ($5\nu_x = 72$). This resonance is driven by a third order sextupole term. The real machine is of course not perfectly symmetric. The resulting β-beating and phase advance errors allow first order sextupole resonances to be excited such as $3\nu_x = 43$.

The effects of symmetry breaking on the behavior of the tails at different tunes is illustrated with the help of phase space plots. Figure 4 shows the normalized horizontal phase spaces next to the $3\nu_x = 43$ and $5\nu_x = 72$ resonances. The left side shows the unperturbed machine, the right side a machine with a rms β-beating of $\approx 5\%$ in the horizontal plane.

Let us first consider the $5\nu_x$ resonance (lower figures): The resonance islands are even visible in the unperturbed case, as expected from the resonance condition of the symmetric machine. These islands remain unchanged when breaking the symmetry. Only the outer part of the phase space (beyond the vacuum chamber aperture) is distorted by the $8\nu_x = 115$ resonance.

In the vicinity of the $3\nu_x$ the situation is completely different. Whereas in the unperturbed case there is no distortion at all, the inner phase space becomes completely distorted by the islands of the 3rd integer resonance.

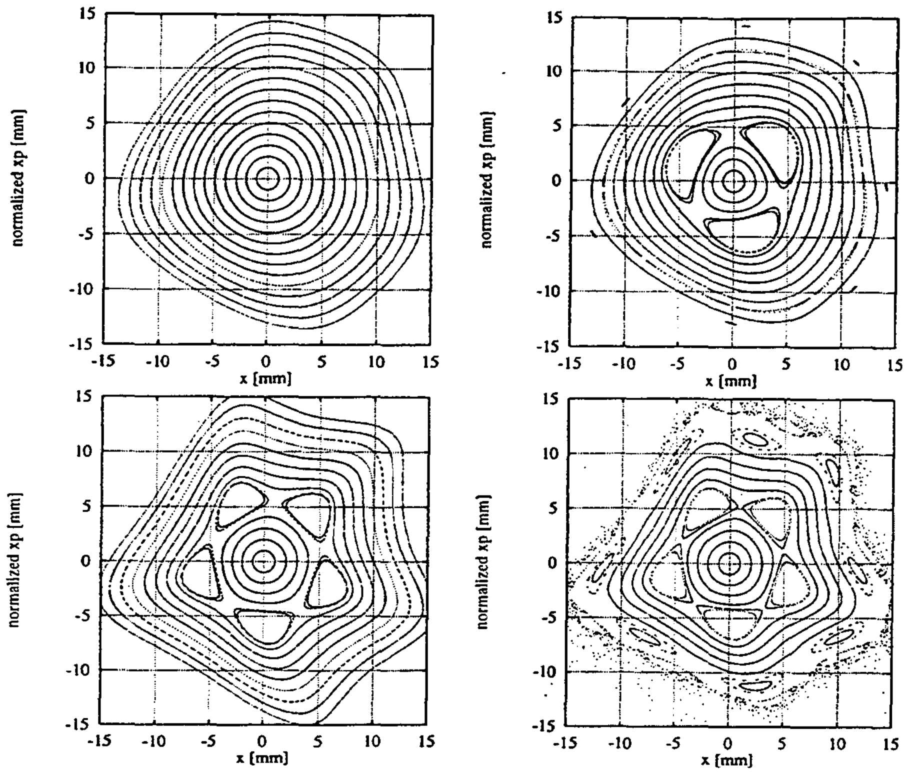

Figure 4. Normalized horizontal phase space in the vicinity of the $3\nu_x = 43$ (upper, $\nu_x = 14.335$) and $5\nu_x = 72$ (lower, $\nu_x = 14.408$) resonances
Left: ideal, unperturbed machine Right: artificial introduced 5% β-beat

In figure 2 we see that the $3\nu_x$ resonance is somewhat excited indicting some symmetry breaking already exists in the "unperturbed machine". In figure 3 we see that as we systematically enhance the symmetry breaking the width of the $3\nu_x$ resonance increases while the width of the $5\nu_x$ resonance remains unchanged when the symmetry is broken. The different behaviors of the observed resonance width of these two resonances is therefore well understood, and agrees with simulations.

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