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The 1991 Dynamic Aperture Experiment at the CERN SPS

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Abstract

This year's dynamic aperture experiment at the SPS concentrated on the study of the diffusion enhancement by tune modulation in presence of strong non-linear fields. The aim of this experiment is to specify an upper limit for the power supply ripple in view of the LHC, the proposed hadron collider in the LEP tunnel. Due to strong, unavoidable non-linearities of the superconducting magnets we expect this accelerator to be very sensitive to power supply ripple. An additional tune modulation, large in comparison with the natural one, was therefore introduced in the SPS and a particle diffusion was measured for several modulation amplitudes. The combined effect of two frequencies with equal amplitude was also tested. In parallel long-term tracking studies have been performed, which allow to find the dynamic aperture for a model of the SPS with the added non-linearities and tune modulations.

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1 Introduction

At the SPS a series of dynamic aperture experiments have been performed [1, 2, 3] to study non-linear particle motion. The SPS is a very linear machine at an energy of 120 GeV, so that it can be made non-linear in a controlled manner by 8 additional strong sextupoles. The sextupoles are powered in such a way that low order effects (1st order resonances) are suppressed and high order resonances can be studied. In this way a situation is investigated that is somewhat similar to the LHC with its large high order multipole errors. In the former studies the tracking studies showed a remarkable agreement with the experiment in a short-term range (seconds). However a slow diffusion process that leads to a particle loss after minutes of storage time was discovered which is not seen in the simulations. We concluded that some other mechanism had to be included in our tracking model, such as power supply ripple. An additional tune modulation indeed causes a decrease of the stability border in the tracking as well as in the experiments. After having found a workable experimental procedure first results were obtained that we compare here with tracking simulations.

2 Experimental Results

2.1 Setting up of the SPS

This year a lot of effort has been done to improve the performance and reliability of the experiment. After having switched the machine to its original optics, the closed orbit correction could further be improved especially for the vertical one, which we got down to .2 mm rms; higher order correction of the nonlinear chromaticity was achieved in an attempt to reduce the tune spread in the beam before the large emittance increase obtained by kicking in the horizontal plane. Active filters on the quadrupole power supplies were introduced to minimise the natural ripple spectrum.

It must be said, however, that we did not yet achieve a procedure that guarantees a reliable and reproducible setup of the machine. In the second part of the experiment the vertical orbit could not be improved to less than 1 mm rms. Even though this value is rather small, it seems to be sufficiently large to activate skew resonances. For this reason the tune had to be shifted slightly to avoid these resonances in the second part of our experiment. Even after the non-linear chromaticity had been corrected the spread in the tunes without kick remained unexpectedly large with roughly $\Delta Q = 5 \times 10^{-3}$, which could not be explained up to now. Moreover in the second part we had trouble to obtain flat beams: an increase of the vertical emittance by a factor of three could not be avoided after the large horizontal kick. After a lot of machine

adjustment especially of the tune, we nevertheless reached a state where the particle loss in the presence of the strong sextupoles only occurred when the tune modulation was switched on.

2.2 Diffusion measurement

After the minimisation of the power supply ripple all ripple frequencies (50 Hz and higher harmonics) stay below $\Delta Q = 2 - 3 \times 10^{-4}$ which is by far below the additional ripple, the depth of which was varied between $\Delta Q = 1.1 - 2.2 \times 10^{-3}$. We used three modulation frequencies (9 Hz, 40 Hz, 180 Hz) which sample the range of interest.

Our turn-by-turn data acquisition system BOSC [4] was used for recording the intensities from the beam current transformer and the betatron oscillations after a kick has been applied. The former can be used to calculate the lifetime, while the former allows the calculation of the tunes via a FFT of the data. These FFTs not only give the tunes, but also allow to picture the spread of the amplitude-dependent tunes and reveal strong resonances (Fig. 1), which lead to dips in the tune distribution.

As discovered last year, the losses were mostly vertical even though the kick was horizontal. Our interpretation is that there is an energy exchange due to non-linear coupling resonances. The experiment requires therefore a rather complicated procedure: after applying the kick and finding the edges of the beam, a horizontal and vertical amplitude is defined by horizontal and vertical scraping; both the scrapers are then retracted (double retraction method) and the diffusion time after which the first scraper is reached by the particles is measured (waiting long enough allows the measurement of a second diffusion from the other plane); finally the scraping is repeated to the same two locations to determine in which plane the diffusion has occurred. Figure 2 shows one of our diffusion measurement for a 9 Hz ripple at a modulation depth of $\Delta Q = 1.1 \times 10^{-3}$ done according to our measurement procedure: after a period of 6.7 minutes (each of the samples of data points correspond to a period of 14.4 seconds), the vertical scraper is reached which leads to a constant decrease of the intensity thereafter. Table 1 shows the measured diffusion for three different modulation depths for a modulation frequency of 9 Hz. The strong influence of the modulation depth on the stability (doubling the modulation depth leads to a decrease of the diffusion time by a factor of 10), has yet to be understood (see next chapter).

In the tracking studies it has been discovered that a second modulation frequency leads to a sizable reduction of the dynamic aperture. We therefore were interested to see if this effect could be seen in the experiment. Figure 3 shows the effect two equally strong frequency modulations (9 Hz and 180 Hz) have on the particle lifetime compared

to a situation of a single frequency modulation (9 Hz). In both cases the total modulation depth was the same, but in the case of two frequencies we find a dramatic decrease of the lifetime: a lifetime of 7 h for one frequency goes down to 2 h for two frequencies. Note that in all cases the lifetime goes to infinity when the tune modulation is switched off. Also in this case we have not yet achieved a quantitative agreement with the tracking simulations.

3 Tracking Studies

3.1 High Order Chromaticity Correction

We started our study with the correction of high order chromaticity to reduce the spread of the tune for the unkicked beams. The expression for the momentum dependence of the tunes, reads

$$Q_{x,z} = \xi_{x,z}\delta + \xi'_{x,z}\delta^2 + O(\delta^3) \quad (1)$$

where $\xi_{x,z}$ and $\xi'_{x,z}$ are functions of the sextupolar gradients. In the SPS there are five families of sextupoles that can be used for such corrections, of which four are necessary to do the simplest of those corrections: that means getting rid of the first two terms in (1) in both planes. A correction was attempted in order to minimize also third order effects, using the five families.

There are several ways to perform this kind of correction. A straightforward approach is by finding the dependence of the tune on momentum via numerical tools [7, 8]. There are also analytic tools such as *Normal Forms* [9, 10, 11, 12] that can provide useful approaches to this problem as showed in [13, 14, 15]. We have chosen this second technique as it allows a general correction even in cases when dependencies other than the momentum play an important role in the correction scheme [16].

The results of our method are shown in Fig. 4. The two curves represent the tune shift dependence on the momentum variation: curve (B) refers to the machine before the correction of the chromaticity effects, while (A) is the corrected machine. This plot illustrates how well a correction of the second order effect can be performed using four families of sextupoles. As it turns out, however, there is a price to be paid for these corrections, which is a sizable β -beat for off-momentum particles. A compromise has therefore to be found between a chromaticity correction and the disturbances due to the β -beat. For instance in case of a third order correction of the chromaticity with five families of sextupoles, a realistic closed orbit spoils completely this high order correction. It is generally wise to restrict a correction in terms of one parameter to a low order, when the system depends also on other pa-

rameters. The corrected system would otherwise become very sensitive, in a high order sense, on those other parameters.

3.2 Diffusion due to Tune Modulation

With the aid of the tracking program SIXTRACK [5] we tracked single particles up to 2.6×10^7 turns (corresponding to ≈ 10 min storage time in the SPS). We first show how the particle stability depends on the modulation depth. In Fig. 5 the upper three dashed curves represent a particle loss over 20 s for the three momentum deviations, while the lower ones indicate the onset of chaos. Both sets of curves show the expected decrease with increasing modulation depth. The decrease in the particle loss is more pronounced, but still weaker than what we found in the experiment (Table 1).

In former studies we found a strong dependence of the chaotic border on the modulation frequency [6]. The chaotic boundaries of the three momentum deviations (the three lower curves in Fig. 6a) show the expected decrease of the dynamic aperture when the modulation frequency is lowered. The actual particle loss before 20 s do not show this dependence, which simply means that the tracking has not been done for a large enough number of turns (compare [3]). Adding the small natural 50 Hz ripple ($\Delta Q = 2.5 \times 10^{-4}$) to cases studied in the upper graph we find a sizable reduction of the chaotic boundaries (roughly 4 mm). The amplitudes at which particle loss takes place before 20 s (Fig. 6b) are reduced as well. Furthermore we find that the strong dependence on the frequency is levelled out and that the particle losses occur at a somewhat lower amplitude. The figure also shows that a large reduction of the stable amplitude (more than 4 mm) is found, when the tracking is prolonged from 20 s to 10 min. It must be noted that some of these losses indeed occur between 2 min and 10 min.

An overview of our tracking results is given in Table 1: for the three modulation depths one finds the amplitudes (a range is given for the three momentum deviations) at which the particles are lost before 20 s, 2 min and 10 min. As a general result it can be stated, that the diffusion in the experiment (14.3 mm) sets in at amplitudes roughly 20 % smaller than those determined in the simulations.

The strong effect of a second frequency, seen both in the simulations and the experiment, is not fully understood up to now. We can, however, propose a qualitative explanation in terms of sidebands produced by the modulation frequencies. In Fig. 7a we show the fast fourier transform of the horizontal motion of a particle under the influence of one tune modulation at 9 Hz with a depth of $\Delta Q = 1.65 \times 10^{-3}$. Adding a second frequency of 50 Hz with a small depth of $\Delta Q = 2.5 \times 10^{-4}$ (Fig. 7b) each of the sidebands in Fig. 7a creates secondary sidebands, so that the width of the distribution of those sidebands becomes wider

(see circles in Fig. 7). Both effects, more peaks and a wider distribution, tend to make the motion more chaotic and consequently the particle loss occurs faster. This can be best understood when two very different frequencies are considered: the smaller frequency lowers the chaotic boundary, whilst the larger frequency, which tends to produce fewer but stronger resonances, provides the mechanism for the particle loss. It is clear that more work has to be done on this subject, especially as this effect of two frequencies seems to be more pronounced in the experiment.

4 Conclusions

The experiment is complicated, as it is very sensitive to adjustments of the machine parameters such as vertical closed orbit. However, once the SPS is tuned well, it can be considered stable in a wide amplitude range even in the presence of strong non-linearities. The diffusion immediately sets in when the tune modulation is turned on and can be measured quantitatively. Another complication is the fact, that even though we kick the beam horizontally the motion has to be treated as a coupled four-dimensional motion, as we loose the beam mostly vertically. A special experimental treatment is therefore required (double retraction method). In a qualitative sense there is no doubt that a power supply ripple which leads to a tune modulation of 10^{-3} can not be tolerated in a machine with strong non-linearities. Moreover we find that a simultaneous tune modulation at two frequencies is by far more dangerous than a modulation with a single frequency for the same overall modulation depth, an effect first seen in our tracking simulations. However, the uncertainties in the experiment do not allow yet a detailed quantitative comparison. We still underestimate the effect of tune modulation by more than 20 % in our simulations. The strong dependance of the diffusion on the modulation amplitude in the experiment and the dependance on the modulation frequency is not yet fully understood. We are, however, confident that the next round of experiments with new experimental and analyzing tools will allow a more satisfying understanding of the complicated but fascinating subject of diffusion in conservative systems.

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	Modulation Depth ΔQ (10^{-3})	1.1	1.65	2.2
Experiment	Diffusion Time (min) at 14.3 mm	6.7	3.1	0.7
Simulations Amplitudes in (mm) of particles lost after time indicated	20 s	19-23	18-23	18-22
	2 min	17-19	17-19	17-19
	10 min	—	17-19	15-19

Table 1: Experimental data and tracking results

Figure 1: Tune distribution for kicked beams

The amplitude-dependent tuneshift is shown for four kick-amplitudes. With increasing amplitude the spread of the tunes becomes wider and the $8Q_x$ resonance is seen as a clear dip in the distribution. Once this resonance sits in the center of the distribution due to a large kick of 19.5 mm a particle loss is observed.

Figure 2: Diffusion measurement

After the retraction of both scrapers in the horizontal and vertical plane the particles need 6.7 minutes to reach the first (vertical) scraper. Thereafter a constant loss in intensities sets in.

Figure 3: Lifetime for one and two modulation frequencies

The lifetime drops from 7 h to 2 h when the same modulation depth is created with two modulation frequencies instead of one. Whenever the tune modulation is switched off the lifetime becomes unmeasurable large.

Figure 4: Momentum-dependence of the tunes

The tunes as a function of the momentum deviation is plotted for the two cases, namely before correction (curve *B*) and after correction (curve *A*). The quadratic part has been cancelled well using four families of sextupoles.

Figure 5: Effect of the modulation depth on particle stability

The particle loss (before 20 s) and the chaos onset as a function of modulation depth are depicted for the three momentum deviations and at a modulation frequency of 9 Hz. Both sets of curves show a clear decrease when the modulation depth is raised. The particle loss, however, is more affected, which is in qualitative agreement with the experiment.

Figure 6: Effect of the modulation frequency on particle stability

The particle loss (before 20 s) and the chaos onset, here as a function of modulation frequency, are depicted for the three momentum deviations and at a modulation depth of $\Delta Q = 1.65 \times 10^{-3}$. Part a.) considers only one frequency, whilst in part b.) the small natural ripple line of 50 Hz is added, showing clearly the destructive effect of two frequencies. Moreover in part b.) the long-term particle loss (up to 10 min) and the diffusion found in the experiment is shown. We conclude that we are still underestimating the effect of power supply ripple in the simulations.

Figure 7: Effect of two frequencies on the horizontal FFT

In part a.) we show the fast fourier transform of the horizontal motion of a particle under the influence of one tune modulation of 9 Hz with a depth of $\Delta Q = 1.65 \times 10^{-3}$. Adding a second frequency of 50 Hz with a small depth of $\Delta Q = 2.5 \times 10^{-4}$ each of the sidebands in part a.) get secondary sidebands, resulting in a wider distribution of sideband peaks (see circles in both parts).