Influence of Power Supply Ripple on the Dynamic Aperture of the SPS in the Presence of Strong Nonlinear Fields

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Abstract

The 1988 SPS Dynamic Aperture Experiment revealed the existence of a slow diffusion process far inside the region which was expected to be stable according to extensive tracking studies. A possible cause for this diffusion is the ripple of magnet power supplies. The effect of ripple which leads to a tune modulation was then studied with tracking varying the modulation frequency and depth. In 1989 and this year the effect of tune modulation on the Dynamic Aperture could be tested experimentally. A controlled modulation of the tunes was introduced by powering a special quadrupole. The modulation depth was larger than the natural modulation measured on the machine, while the frequency could be varied between 1Hz and 200Hz. In the presence of strong nonlinearities introduced by special sextupoles the diffusion was measured as a function of beam diameter, modulation frequency and depth.

Introduction

Since 1986 dynamic aperture experiments[1,2] have been performed on the SPS to study the effect of strong nonlinearities on the stability of particle motion in proton accelerators.These experiments aim at understanding how the strong multipolar errors that are to be expected in the superconducting magnets of the LHC will affect the dynamic aperture of such a machine. One hopes to establish a criterion that ensures particle stability without the need of tracking simulations over millions of turns. To this end a quantitative comparison of the results of a controlled experiment with the corresponding tracking simulation is necessary.

The SPS is well suited to these investigations as it is a very linear machine at a medium energy of 120 GeV, while the strong sextupoles normally used for ejection at high energy can be powered to introduce a strong source of nonlinearities. Moreover the excitation of the sextupoles can be chosen so as to largely suppress the first order sextupole resonances, leaving higher order effects similar to those which will dominate the performance of the LHC. So far the experiments could be well understood as far as short term effects (developing over a few seconds) were concerned.[3]

In 1988 it was however discovered[4] that sextupole nonlinearities are also responsible for a long term diffusion process leading to sizeable particle loss over a period of a few minutes. This phenomenon invalidated our proposed stability criterion.

It is therefore mandatory to understand where the diffusion stems from. One possible source is the tune modulation due to the residual current ripple of the quadrupole power supplies, which has been known for a long time to increase particle losses in the presence of nonlinear resonances.

Results obtained in 1989 at both FERMILAB[5] and the CERN SPS[6] indeed showed that tune modulation does influence the dynamic aperture in the conditions of these experiments.

This year's experiment at the SPS was intended to provide results that allow a quantitative comparison with tracking simulations. It turned out however that the experiment was more difficult to perform than initially anticipated, so that different techniques had to be tried out until we finally found the appropriate experimental procedure.

Simulations with tune modulation

In the absence of tune modulation the long term diffusion found in the experiment could not be explained by tracking: long term tracking as well as the Lyapunov exponent method[7] to detect chaotic motion predict perfect stability. In the SPS there is however a tune modulation, which is caused by the imperfections of the quadrupole power supplies. Considering this tune modulation in the tracking a strong reduction of the dynamic aperture can be found especially for low frequencies[8], which does not affect however the short term behavior (10^3 to 10^4 turn stability) very much.

This tune modulation causes a very slow instability (10^6 turns are needed to find the onset of chaotic motion). The survival time in the SPS of these particles which exhibit chaotic behavior in an amplitude range between the short term dynamic aperture and the long term stability border remains to be evaluated.

As tracking studies for this machine over 10^7 turns would be too time consuming to clarify this point a simple 4D Henon-Heiles map with tune modulation was studied instead to allow at least a qualitative understanding. Figure 1 shows the survival plots for 9Hz and 200Hz modulation frequencies compared to the situation with no modulation.

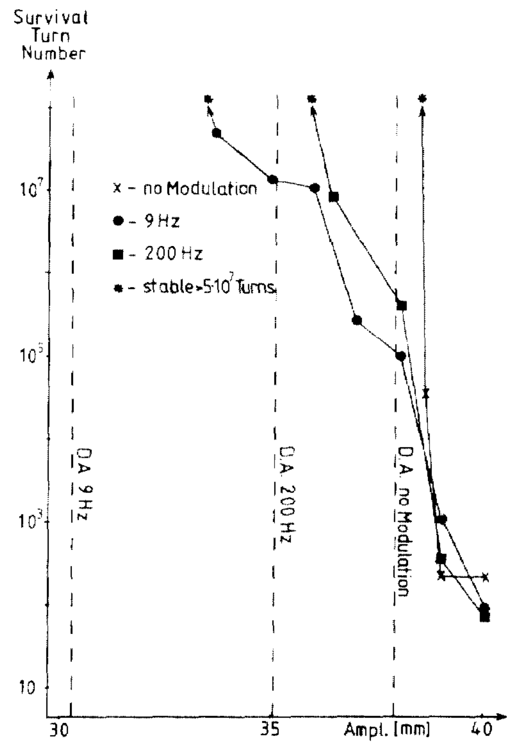

Figure 1 Long term behavior due to tune modulation

The dynamic aperture (D.A.) obtained via the Lyapunov exponent method is strongly affected by tune modulation, the lowest frequencies having the strongest effect. One finds however that up to a high number of turns (10^5) all three survival curves lie close together; it takes 10^6 turns to see the influence of tune modulation; after 10^7 turns the curves relative to the two frequencies start to depart and even 5 x 10^7 turns are not enough to reach the stability border in the case of 9Hz. Note that only 2 x 10^4 turns are sufficient to find this border using the Lyapunov exponent method in this simple case.

From the above we have seen that tune modulation indeed causes a slow particle instability. A quantitative evaluation of how slow this effect is and wether one can actually find the frequency dependance via particle loss for a real machine like the SPS remains to be seen.

Experimental Setup

The goal of this year's experiment was to get quantitative results which can be compared with tracking. To achieve this it was necessary to impose an additional modulation with a modulation depth large compared to the natural one and with variable frequency. We found using our continuous Q-measurement system[9] that for all imposed modulation frequencies a depth of $\Delta Q = \pm 8 \times 10^{-4}$ was 3,5 times stronger than the natural one.

In 1988 the diffusion was studied as a function of amplitude with the so called retraction method, which uses scrapers to define amplitudes with respect to the beam center. The diffusion time is that period during which a long (hopefully infinite) beam lifetime can be measured after the scrapers have been retracted by 2 to 3 mm.

The recent experiments using this method were found to be more difficult than expected. However after many trials an efficient experimental procedure was devised. The first step consisted in a careful correction of the closed orbits (from an r.m.s. deviation of 4mm down to 1.8mm). This considerably reduced the linear coupling induced by the vertical closed orbit deviations in the sextupoles, which could then be further corrected using skew quadrupoles so that a minimum tune approach of $\Delta Q = 0{,}005$ was obtained. In these conditions the particle losses to the limited SPS vertical aperture were minimized. The tune spectrum was recorded repetitively using the Schottky receiver to optimize the working point in the tune diagram and to identify the effects of resonances. Octupoles were used to decrease the amplitude dependent tuneshift so as to better locate the working point in between the most dangerous resonances. The intensity was recorded in parallel with a chart recorder and with the BOSC system[10] which allows an on-line calculation of the beam lifetime. For the retraction method scraping in the two planes was necessary both before and after the retraction to understand in which plane the diffusion had taken place.

Results

a.) Detuning Compensation

The measurement of the amplitude dependent tuneshift which had been found to be in good agreement with tracking in the previous experiments[2] was done again. Figure 2 shows that the experimental results obtained this time are in very good agreement with the data of 1988.

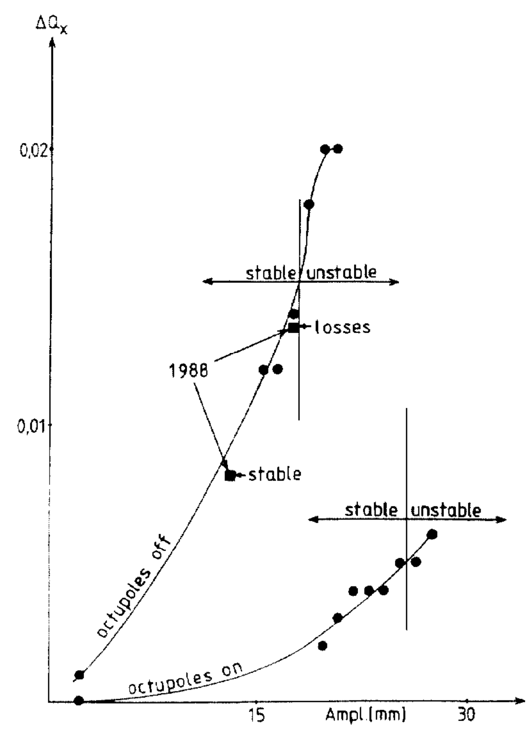

Figure 2 Measured detuning and dynamic aperture as a function of amplitude, without and with octupole compensation

Moreover figure 2 shows clearly how strongly the nonlinear behavior of the machine can be influenced by the use of octupoles. By adequately powering the SPS octupoles we succeeded in reducing the nonlinear detuning by a factor of roughly 10 which at the same time improved the dynamic aperture by 30%. This gives us confidence that correcting the nonlinear tuneshift in the LHC[11] is the appropriate method to improve the performance of this very nonlinear machine.

b.) Setting up the Diffusion Experiment

The diffusion rate was measured by the retraction method after having increased the horizontal beam size up to the dynamic aperture by a horizontal fast deflection (kick) of 17,6mm amplitude (all amplitudes are normalized at $\beta = 100$m). Figure 3 shows the beam profile obtained in this way.

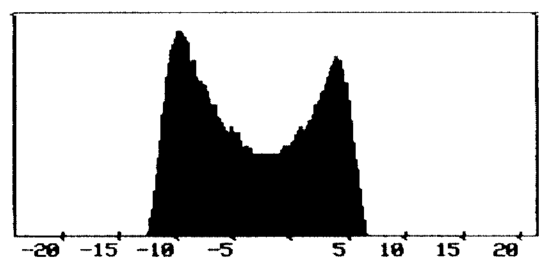

Figure 3 Wire scanner beam profile after kicking

A measurement was first taken with no tune modulation, and then with tune modulation at three different frequencies (9,40,180Hz) and the same modulation depth of $\Delta Q = 8 \times 10^{-4}$.

The tune was adjusted so that most of the particles stay away from the 5th and 7th order resonances ($Q_H = 0{,}623$-$0{,}640$, $Q_V = 0{,}529$-$0{,}540$) after applying the kick. Figure 4 shows the frequency spectrum at the start and end of the measurement (9Hz modulation). One can see the shrinking of the distribution for tunes corresponding to particles at large amplitudes (the right side of the Q_H and the left side of the Q_V distribution respectively). The small peaks on the left side of each distribution, which appear at the end of the measurement are due to the $3Q_H + 2Q_V$ resonance.

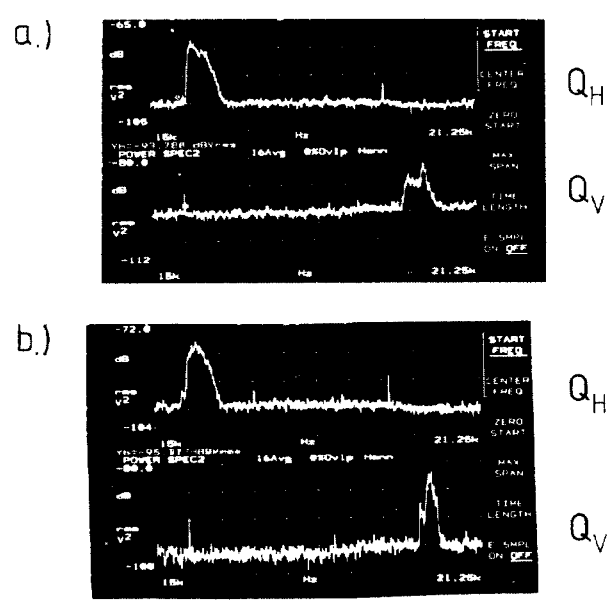

Figure 4 Tune distributions at the beginning (a) and at the end (b) of the experiment

c.) Results for the Diffusion Experiment

As we retract the scrapers in both planes we expect first a period of very large lifetime before the particles reach the scrapers. When the first scraper is reached a drop in the lifetime is noticed. This is followed by a second drop when the second scraper is reached. This is indeed what we see in figure 5 which shows the case with no modulation: the first drop occurs after 5 minutes, the lifetime τ_1 being 80 hours before and τ_2 = 14,5 hours after. The second drop occurs after 14,2 minutes, the lifetime decreasing then to τ_3 = 6,3 hours.

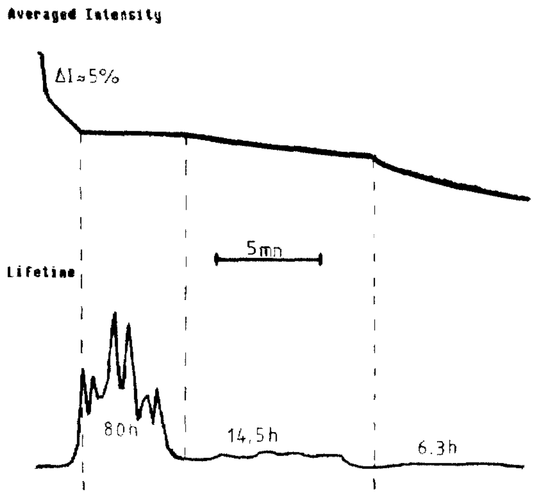

Figure 5 Diffusion measurement using scrapers

The diffusion seems to be dominant in the horizontal plane, since only the horizontal retraction leads to a plateau of large lifetime. It was also found that putting the scrapers back to their original location at the end of the measurement produces a loss of only 1% in the vertical plane while typically 3% are lost in the horizontal plane. In table I the calculated lifetime and diffusion rates are recorded for all cases with two different positions of the scrapers (H and V). Two diffusion rates, D_1 and D_2, can be obtained from the time taken to reach the scrapers.

Table I Lifetime and Diffusion rates

	Scraping: H:=horizontal; V:=vertical									
	H = 14,4 mm ; V = 11,4 mm					H = 13,7 mm ; V = 10,6 mm				
Modulation	τ_1 [h]	D_1 $[\frac{mm\,mm}{mn}]$	τ_2 [h]	D_2 $[\frac{mm\,mm}{mn}]$	τ_3 [h]	τ_1 [h]	D_1 $[\frac{mm\,mm}{mn}]$	τ_2 [h]	D_2 $[\frac{mm\,mm}{mn}]$	τ_3 [h]
off	82,0	0,54	14,5	0,21	6,3					
9 Hz	14,0	5,6	4,6	1,1	3,3	21,0	2,3	5,7	0,75	3,5
40 Hz	25,0	2,5	6,7	0,6	3,5	63,0	2,3	7,2	0,63	4,8
180 Hz	45,5	2,8	3,3	0,5	2,4	>60,0	2,5	6,0	0,71	3,4

In the first scraping position the diffusion is apparently faster for lower frequencies, which is expected from the tracking results. However in the second scraping position where the different lifetime regimes are more easily distinguished the results are the same for all three modulation frequencies.

What is beyond doubt is that the modulation strongly affects the stability, the diffusion being 5 to 10 times faster with modulation than without.

Conclusions

A major outcome of this experiment is that the octupoles which are used to decrease the nonlinear detuning are very effective in enlarging the stability region.

For the diffusion experiment we have found an efficient experimental procedure and adequate instrumentation. A complete set of data including lifetimes and diffusion rates with and without modulation is available, so that a quantitative comparison with tracking is now possible.

The importance of tune modulation for particle stability is well established, while the question of the frequency dependance of the modulation on the dynamic aperture still needs clarification.

Acknowledgements

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