Dynamic Aperture and long term particle stability in the presence of strong sextupoles in the CERN SPS

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ABSTRACT

The reduction of dynamic aperture produced by strong sextupoles has been measured in the SPS. The short term aperture, inside which particles survive for at least one second, is well predicted by computer simulations based on the early detection of chaotic motion. Inside this aperture particles diffuse slowly to larger amplitudes, so that long-term stability is only assured in a smaller region of the phase space, the long-term aperture. Slow tune modulations increase the chaotic regions and could explain the observed diffusion phenomena. The criteria based on tune shift and smear which are used in the design of Large Hadron Colliders are discussed.

INTRODUCTION

In 1986 experiments had been performed on the SPS to evaluate the reduction in dynamic aperture produced by strong sextupoles[1]. The aim of these experiments was to check the validity of the empirical criteria used in the design of the CERN large hadron collider, which require that the "smear" be smaller than 0.035 and the detuning ΔQ smaller than 0.005. This effort concentrated mainly on the determination of short term effects, those which can lead to particle losses over a few seconds, that is after about 10^5 revolutions.

The new experiments which are reported here mainly investigate long term aspects of the influence of non-linear fields, those which may induce a slow diffusion in the tails of the beam distribution, thus leading to a deterioration of the beam lifetime[2]. In addition, a new data acquisition system has been used to explore the non-linear phase space by deflecting a pencil beam to large amplitudes and measuring the response of two transverse pick-ups[3].

The experimental conditions were the same as in ref.1: strong sextupoles normally used for slow ejection were powered in such a way as to excite high order betatron resonances, while minimizing the effect on the nearest 1/3 order resonance and leaving chromaticity undisturbed to first order. Measurements on the beam were made at an intermediate energy of 120 GeV, either on a magnetic flat top of 8 seconds duration in pulsed mode, or during a few hours coast at the same energy.

Experimental results have been compared to computer tracking using PATRAC[4] and SIXTRACK[5].

EXPLORATION OF THE PHASE SPACE AND SHORT-TERM DYNAMIC APERTURE

This part of the experiment was carried out in pulsed mode, on an 8 sec. long flat top at 120 GeV. The beam was the same as for fixed target operation (the whole SPS circumference is filled by two consecutive CPS batches) apart from the intensity which was reduced in the CPS so that about 2.10^{12}p were injected at 14 GeV/c in the SPS. The transverse emittances were reduced by scraping in the horizontal plane: this produced a pencil beam with an r.m.s. radius of 1.3 mm, a good probe to explore the available phase space which extends to an amplitude of about 17 mm in the horizontal plane in the presence of the additional sextupoles*. At the beginning of the flat top the sextupoles were energized and the beam kicked horizontally by firing one module of the fast kickers normally used for fast ejection at high energy.

Two different working points have been used, and can be seen on fig. 1. The dot indicates the tunes measured at small amplitude, while the cross represents the stable particle with the largest amplitude. Point 1 has been chosen to explore a region where the 5th order resonances are likely to dominate, while in point 2 the beam is free of resonances of order less than 7.

In figure 2 the continuous curve shows the variation of the horizontal tune as a function of the horizontal amplitude as determined by tracking, while the dots represent the values obtained by Fourier analysing the turn by turn pick up signals of the kicked beam. One sees that there is a very good agreement between the values measured and those obtained by simulation. Figure 2 represents the case of working point 1 with sextupoles energised to 140A. Data were also gathered for point 2 with 140A as well as 250 A in the sextupoles, and the agreement between measured and simulated tunes is equally good in these cases[3].

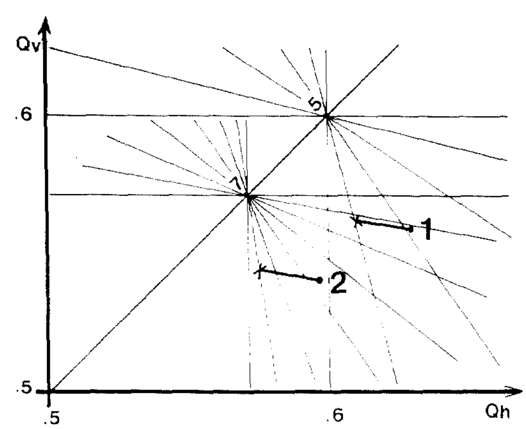

Fig. 1 : Working points

Sixtrack determines the boundary between regions where the motion is regular and regions where the motion becomes chaotic. For this it tracks two particles with slightly different initial conditions. In a regular region of phase space the phase difference between the two particles increases linearly with time, whereas in a chaotic region it tends to increase exponentially. Figure 2 shows that the first manifestation of chaos appears at an amplitude of 17.8 mm.

Experimentally part of the beam was lost when a kick of 17.6 mm was applied whereas no loss occurred with a kick of 13.2 mm. In the first case, since the

*Beam radius and deflection amplitude are expressed as if measured at a location where ß = 100 m, unless otherwise stated.

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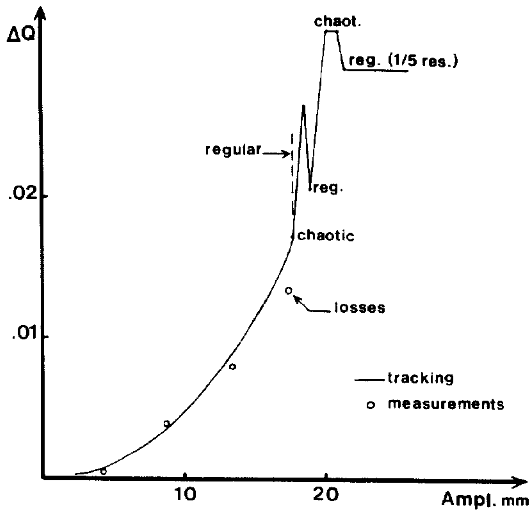

Fig. 2 : Tune shift and stability

r.m.s. radius of the beam before kicking was 1.3 mm, about 98% of the particles had after the kick, an amplitude smaller than 20.2 mm (kick amplitude + 2σ of initial beam) and this value can be used to define the "edge" of the beam. In the second case the edge of the beam was at 15.8 mm. The observed behaviour is therefore very much consistent with the chaotic boundary as determined by simulation in Sixtrack. The cases of the other working points, which are displayed in table 1, confirm this impression.

Table I: Chaotic boundary and beam losses

	Chaotic boundary (Sixtrack) (mm)	kick amplitude (mm)	Edge of beam (mm)	Losses
point I	17.8	17.6	20.2	Yes
140A		13.2	15.8	No
point II 140A	20.6	17.6	20.2	No
point II	7.5	8.8	11.4	Yes
250A		4.4	7.	No

SEXTUPOLE INDUCED DIFFUSION

Up to now the most spectacular effects of non linear forces in colliders did not arise from the imperfections of the guiding field, but rather from the beam-beam interaction. Early experience at the S$\bar{\text{P}}$PS showed that in the presence of localized beam-beam collisions particles tend to diffuse transversely out of the beam, the diffusion rate being faster in the tails of the distribution than in the core.

In the context of the studies for the design of large superconducting hadron colliders, an important issue is whether the unavoidable non-linearities in the guide field are likely to create a similar diffusion mechanism. Although field non-linearities and beam-beam both create tune spread and excite resonances, the situation is quite different in the two cases, in particular because the dependence on particle amplitude is different.

In this experiment the beam was stored at 120 GeV/c and the sextupoles were energized. Then the horizontal beam emittance was slowly increased by repeatedly firing the kicker used for Q measurement, until a few percent losses were noticed.

Figure 3 illustrates the experiment in the case of working point 1. When a scraper was introduced at an amplitude of 15.4 mm about 1% of the beam intensity was lost. Subsequently the 1/e decay time stabilized at about 40 minutes. When the scraper was then retracted by 2.7 mm, the intensity remained constant for 30 seconds, which is the time it took for particles to fill the gap, and then decayed with a characteristic time of 65 minutes. When the scraper was moved back to its initial position, 1% of the beam was lost again and the decay time became 36 minutes, a value close to the initial 40 minutes. We see clearly the signature of a <u>diffusion process.</u>

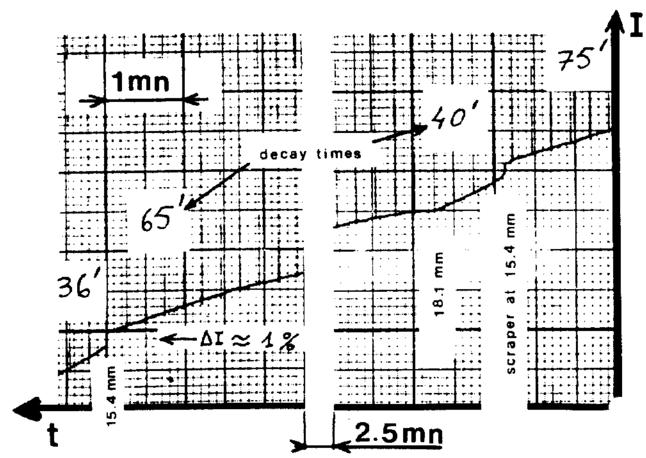

Fig. 3 : Measurement of diffusion rates

The measured diffusion rate was 3 mm/mn at an amplitude of 12.6 mm, and 6 mm/mn at 15.4 mm. At 18.1 mm it was so large that it could not be measured with the procedure described above: this is beyond the short-term dynamic aperture. Similar measurements were done for working point 2, and in this case the largest amplitude at which no significant diffusion could be detected (the "long term dynamic aperture") was determined (9.2 mm).

The measurements were repeated in the absence of the added sextupoles. There was no sign of diffusion up to an amplitude of 22 mm, well outside the dynamic apertures measured in these experiments.

As in the first series of experiments, the measured short-term apertures are well predicted by computer tracking [2,3]. However, long-term tracking for up to 10^6 revolutions did not reveal any chaotic motion inside this aperture, in contradiction with the diffusion measurements. This changed dramatically when a realistic tune modulation ($\hat{\Delta Q} = 3.10^{-3}$) was introduced[6]. Figure 4 shows how chaotic motion invades the phase-space down to lower and lower amplitudes when the frequency of the modulation is decreased. This is to be expected from the application of the Chirikov-Courant criterion for overlap of satellite resonances (see, for instance, ref. 7). Note that the short-term dynamic aperture, determined here by particle loss after 10^3 to 10^4 turns, does not change much when modulation is introduced, and shows no frequency dependence. Another interesting feature is revealed by the evaluation of the Liapunov exponent in the chaotic region: as the particle amplitude decreases the Liapunov exponent increases, and from this lower and lower diffusion rates can be expected. This is in qualitative agreement with experimental observations.

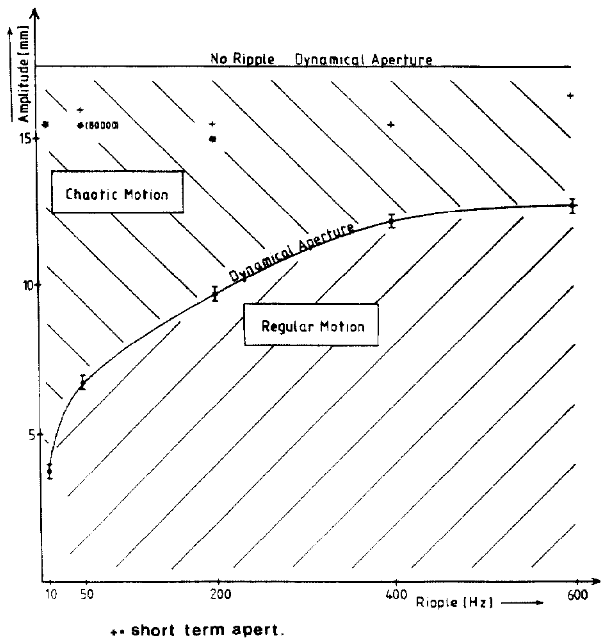

Fig. 4 : Influence of tune modulation

COMPARISON WITH LHC CRITERIA

The results of this experiment are summarized in fig. 5, together with those already obtained in 1986. The points displayed represent the values of ΔQ and smear obtained by simulation and corresponding to the measured short term dynamic aperture (triangles, squares and dots) or to particle amplitudes at which the diffusion rate has been measured (crosses). For the 1986 results, the smear was defined as the variance of the sum of the horizontal and vertical Courant-Snyder "invariants". For the 1988 experiment the definition had to be changed because the closed orbit deviations measured in the machine were introduced in the tracking models, inducing linear betatron coupling in the sextupoles: the four dimensional invariants are now used instead[8].

Two classes of points can be distinguished: the first one corresponds to the 1986 experiment in which the 1/3 order resonance was excited (triangles) while the other corresponds to experiments in which the excitation of the 1/3 order resonance was minimized. In the first case the values of the smear are large (this is to be expected from a largely triangular phase space), while the ΔQ is small at the dynamic aperture. The reverse is true for the second category, with large values of ΔQ and small values of the smear at the dynamic aperture.

The rectangular box in fig. 5 represents the criteria used for the acceptance tests of the LHC lattice: it is supposed that inside this rectangle the machine will be sufficiently linear to assure a good, comfortable operation. In the conditions of these experiments it is clear from fig. 5 that the LHC criteria are conservative as far as the short term dynamic aperture is concerned. However, they are not sufficient to ensure a good lifetime in coast mode.

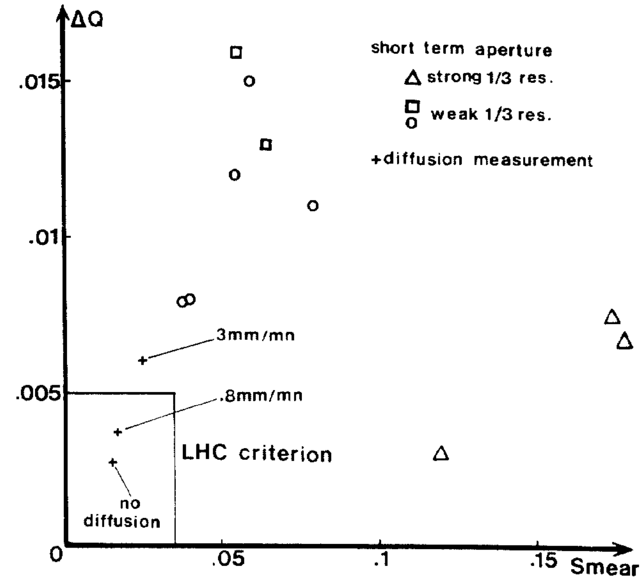

Fig. 5 : Tune shift and smear at the dynamic aperture.

CONCLUSION

The short-term dynamic aperture, which can be easily determined by tracking, is an insufficient concept for the design of superconducting colliders. Criteria based on the value of smear and ΔQ were used up to now as a complement, but in the experiments reported here they fail to ensure long-term stability. Further work is therefore needed to define more suitable criteria in realistic situations.

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