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PRECISE DETERMINATION AND COMPARISON OF THE SPS DYNAMIC APERTURE IN EXPERIMENT AND SIMULATION

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PRECISE DETERMINATION AND COMPARISON OF THE SPS DYNAMIC APERTURE IN EXPERIMENT AND SIMULATION

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Abstract

The combined effect of nonlinear fields and tune ripple can lead to chaotic motion and particle loss in proton accelerators thereby limiting the dynamic aperture of these machines. The SPS Dynamic Aperture Experiment is performed to study a controlled nonlinear machine under the influence of power supply ripple. To this end eight strong sextupoles are used to make the SPS nonlinear. The tune ripple is introduced with one special quadrupole which allows to vary the ripple frequency and depth. In parallel long-term element-by-element tracking is done to investigate its applicability for the estimation of the dynamic aperture of a real accelerator. The influence of non-linear magnetic fields and tune ripple is observed at two working points using a flying wire of 8μm diameter. The experimentally determined dynamic aperture is compared with survival plots obtained from the tracking and their differences are discussed.

I. INTRODUCTION

Non-linearities of superconducting magnets, which cannot be completely avoided, may limit the dynamic aperture of accelerators. It is therefore of great interest to predict the stability range due to these non-linearities. The SPS Dynamic Aperture Experiment is used to compare experimental results with tracking which serves as the predictive tool in this study.

After calibrating the instrumentation we have carefully measured the detuning curves as a function of betatron amplitude and compared them with tracking results. An even modest disagreement between the two would cast doubt on the validity of the model.

We will report about measurements and calculations for the dynamic aperture of the SPS with the following machine set up: coasting beam at 120GeV, closed orbit correction with horizontal and vertical rms below 0.3mm, linear coupling compensation up to $|Q_h - Q_v| = 0.002$, momentum spread $\Delta p/p \approx 10^{-3}$, chromaticity in both planes corrected to $\Delta Q/(\Delta p/p) \approx 1$. Strong non-linearities are introduced by 8 powerful sextupoles. The natural tune ripple spectrum contains 7 major lines that add up to a total amplitude of $0.5 \cdot 10^{-4}$. We studied the working points (Q_h, Q_v)=(26.637,26.533) and (26.605,26.538) referred to as WP1 and WP2 respectively (see Fig. 1). The artificial tune ripple, introduced by a single quadrupole, had a frequency of 9Hz and an amplitude of $\Delta Q_h = 1.87 \cdot 10^{-3}$ and $\Delta Q_h = 0.55 \cdot 10^{-3}$ at WP1 and WP2 respectively. The ratio of horizontal and vertical ripple depth is $\Delta Q_h/\Delta Q_v = 1.75$. The beam is kicked horizontally until the aperture is reached.

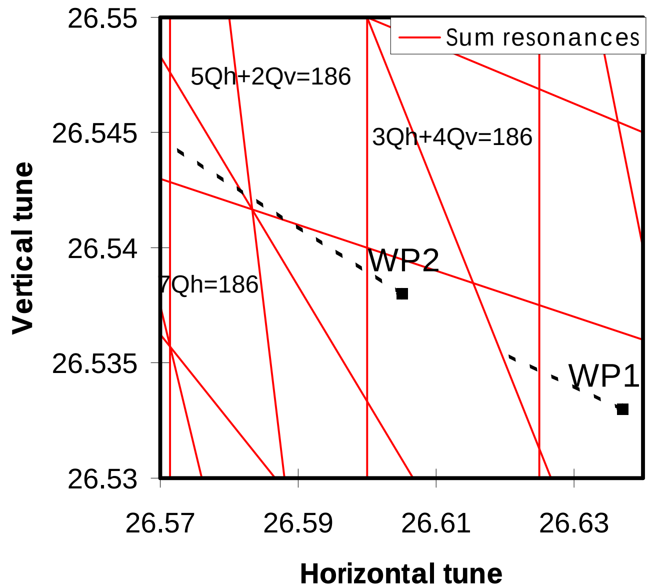

Figure 1. Tune diagram with sum resonances up to order 11 and both working points before and after the kick. The detuning is directed towards smaller horizontal and larger vertical tune values. At the last tune values large scale losses take place.

II. INSTRUMENTATION AND DETUNING

Preconditions for these experiments are an exact knowledge of the applied kickstrength and a high precision of the wire scan readings. The kicker has been calibrated several times and shows a very linear behavior down to small kick amplitudes. Whereas the measurement of 1993 showed a degradation of 10% compared to earlier measurements, the calibration of 1995 showed practically no difference to the measurement of 1993.

The kicked beam is observed by a flying carbon wire of 8μm diameter and 0.4m $\cdot$ s^{-1} speed. The position of the wire can be measured via an opto-electronic ruler with a resolution of 16μm. The intensity of the kicked beam is reduced by $1.4 \cdot 10^{-4}$ per scan (in and out scan) but no beam blow up can be observed. The kicked beam produces a typical double peak structure in the wire scan profile (Fig. 3).

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The kick strength calculated from the distance between the peaks agrees within 10% with the kicker calibration. These beam profiles were also compared with scans from flying wires at different locations. The agreement amounts to some 5-10% which also increases our confidence in the knowledge of the β-functions around the ring.

An important test for a nonlinear accelerator model is the dependence of the tunes on the betatron amplitudes. In the SPS the horizontal and vertical detuning is measured as a function of the horizontal betatron amplitude. The tunes are computed from up to 8192 turns after the kick by FFT and phase advance averaging leading to a precision of $5 \cdot 10^{-4}$ [1]. Fig. 2 shows the comparison of the measured and calculated detuning. The agreement is very good up to large amplitudes and the dependence of the detuning on action ($\frac{x^2_{max}}{2 \times \beta_h}$) is predominantly linear as expected from second order perturbation theory.

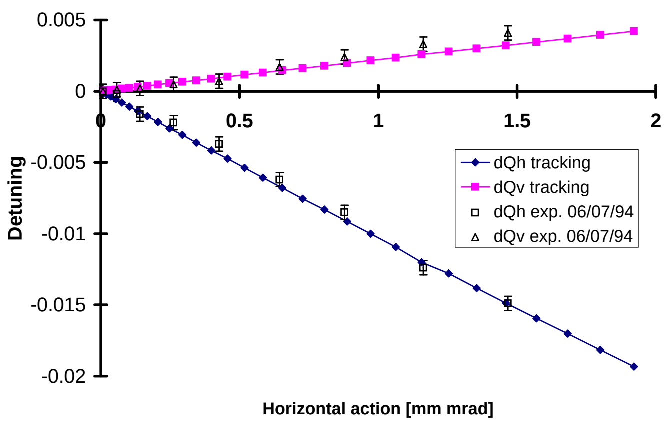

Figure 2. Detuning measured at working point 1.

III. DYNAMIC APERTURE

For practical reasons the dynamic aperture can be defined as stability limit after a certain time interval which may depend on the type of machine and operational considerations. A typical problem is to keep the beam circulating several minutes during the injection period when nonlinearities and beam size are usually at their maximum. In the experiment the observation was done up to 1000s whereas with computer tracking only 345s (15 million turns) could be reached with reasonable computing effort.

A limitation of the SPS experiment is the rather large natural size of the beam before kick. This precludes any fine exploration of the amplitude distribution as is done in tracking. In particular small chaotic regions within an otherwise stable part of the distribution cannot be detected. However the maximum amplitude above which no particle survives after a certain time gives a good measurement of the stability limit.

A. Measured

Experimentally, the dynamic aperture is determined from the maximum bottom width of the wire scan profiles (Fig. 3). At the edge of the beam profile $5 \cdot 10^7$ protons (10^{-4} of the intensity) can clearly be detected. In most

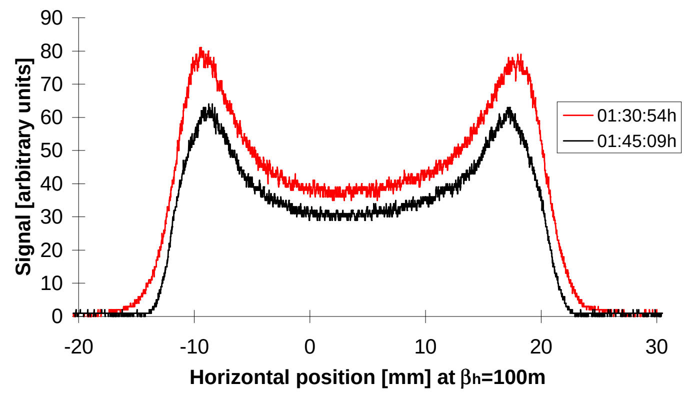

Figure 3. Evolution of the wire scan profile at WP1, tune ripple of 9Hz and $\Delta Q_h = 0.00187$ (#78, no horizontal scraping).

cases 15 scans have been taken at time intervals of about 1min.

In Fig. 4 four wire scan measurements at WP1 with artificial tune ripple are depicted. These curves have been smoothed and the estimated error bars are shown in case #91. The reproducibility of the experimental results has been found to be within 2% for two measurements under the same conditions but 5 months apart (#62 and #76). Due to the rather large beam size the results depend on the measurement procedure: cases #62 and #76 have been scraped horizontally after kicking, whereas cases #78 and #91 are left unscraped and in addition the latter case has been kept for some extra 15min without artificial tune ripple. Although these cases strongly differ initially, after 345s the differences reduce to about 5%.

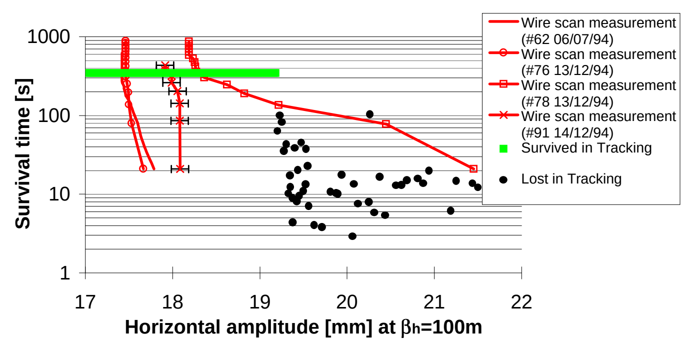

Figure 4. Dynamic aperture at WP1, tune ripple of 9Hz and $\Delta Q_h = 0.00187$.

Fig. 5 shows one of the two cases with natural ripple only. The results of all measured cases are summarized in Tab. I.

B. Computed

The computer code SIXTRACK [2] has been used for the tracking studies. The model included all sextupoles and horizontal and vertical closed orbit, as well as the tune ripple. Tunes, chromaticities and linear coupling are adjusted similar to what is measured in the SPS. As the beam is kicked horizontally the particles are tracked with large horizontal displacements. Moreover, a vertical displacements

Table I

Comparison of measured and computed dynamic aperture. All values are given for β_h =100m. For the onset of chaos there are two values: the larger one is the border above which no regular particles could be found, the lower (in brackets) is the lowest amplitude at which large scale chaotic motion sets in.

case	measured dynamic aperture [mm]	onset of chaos ($2 \cdot 10^5$ turns) [mm]	loss border ($1.5 \cdot 10^7$ turns) [mm]	comparison between measurement and loss border [%]
WP1, natural ripple only	20.0	(15.7) 23.1	24.4	22
WP2, natural ripple only	20.9	(9.8) 23.6	25.7	23
WP1, 9Hz, $\Delta Q_h = 1.87 \cdot 10^{-3}$	17.4	(7.7) 14.3	19.2	10
WP2, 9Hz, $\Delta Q_h = 0.55 \cdot 10^{-3}$	19.5	(7.4) 8.3	22.3	14

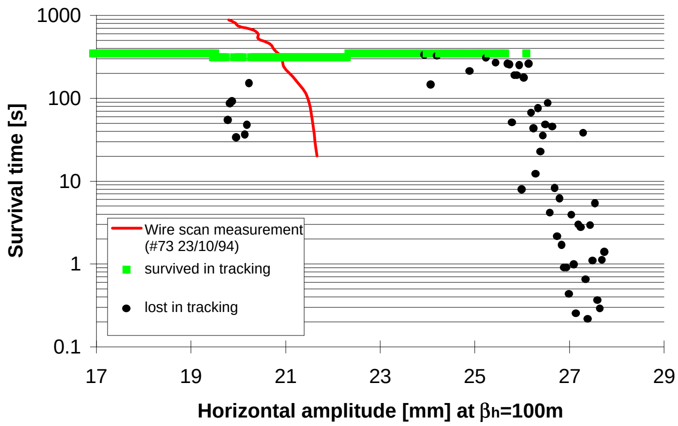

Figure 5. Dynamic aperture at WP2, natural ripple only.

of roughly one σ of the vertical beam size has been considered. In all tracked cases a wide amplitude range could be found (column three in Tab. I) where chaotic (after 200,000 turns) and regular regions alternate. For each chaotic region in that amplitude range a particular sum resonance is found which apparently causes the unstable behavior. In Fig. 4 the lost particles correspond to a coupled 7^{th} order resonance, in Fig. 5 the losses at large amplitudes correspond to the horizontal 7^{th} order resonance and the losses at about 20mm are due to another coupled 7^{th} order resonance (for both cases see Fig. 1).

The dynamic aperture as defined above and computed by long-term tracking is shown in column four in Tab. I. The last column in Tab. I shows the difference in percent between the computed and the measured dynamic aperture. In the cases with additional ripple the difference is about 10% but without ripple this deteriorates by about a factor of two. Moreover in the tracking we find a broad region of apparently regular motion outside of the experimental stability border (not present in the cases with additional ripple). From this we have to conclude that an essential destabilizing effect is missing in our tracking model. A very rough estimate for the scale of this effect is the additional tune ripple because the experimental dynamic aperture without extra tune ripple agrees well with that of the tracking when this ripple is introduced (compare the first two entries in column two with the last two entries in column four of Tab. I). The nature of this effect is still unknown. However, neither some neglected systematic non-linearities nor extra tune ripple are likely candidates. The former would lead to measurable detuning with amplitude, while for the latter the tune ripple can be understood from measured voltage ripple of the SPS power supplies [3] and in addition it has been measured with good precision with a phase-locked loop.

IV. CONCLUSION

The detuning with amplitude of the SPS with controlled strong sextupoles can be well reproduced with our tracking model. We also know to a good precision the tune ripple induced by power supplies. When an additional and sizeable tune ripple is applied the tracking model gives a value for the dynamic aperture which is about 10% larger than the experimental one. However, the cases without extra ripple reveal a more prominent difference (larger than 20%) between the theoretical and experimental dynamic aperture. We address this to some neglected and at present unknown effect which should be about as effective as tune ripple of some 10^{-3}.

V. ACKNOWLEDGMENTS

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