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Experimental Techniques and Observations of Nonlinear Dynamics in Particle Accelerators

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Abstract. Experimental techniques and observations of nonlinear dynamics in particle accelerators since the invention of the phase-space monitor in 1985 are briefly surveyed. To show recent achievements in experimental techniques and observations of nonlinear dynamics in lepton machines, a series of beam experiments conducted at the TRISTAN MR during the autumn of 1993 are presented. The treated issues are the dynamic aperture with tracking results, the amplitude-dependent tune shift, the beam-based measurement of errors and so on.

OVERVIEW

The phase-space monitor, which provides Poincaré maps of the beam motion in real machines, similar to particle tracking in computers, was invented at SPEAR in 1985 using a pair of turn-by-turn position monitors.⁽¹⁾ It clearly demonstrated the phase-space structure near to the 3-rd integer resonance. Since then, it has greatly stimulated unified studies of theoretical and experimental nonlinear dynamics in particle accelerators.

In 1989 on the occasion of the International Conference on High Energy Particle Accelerators, several studies utilizing the phase-space monitor were reported: the observation of higher order resonances up to the 24-th order in the CERN-PS, and resonance assignment by converting the phase-space from (x, p_x, y, p_y) into $(\theta_x, J_x, \theta_y, J_y)$;⁽²⁾ a trial to measure the lattice non-linearity through nonlinear filamentation in the TRISTAN MR (actually, it failed because of a head-tail effect), and the suggestion of a possible measurement of an instantaneous tune;⁽³⁾ the observation of a 3-rd integer resonance, and a comparison of its dynamic aperture with a calculation at ALLADIN;⁽⁴⁾ the amplitude-dependent tune shift and dynamic aperture in the CERN SPS, and the effect of tune modulation on the beam lifetime with/without sextupoles in the TEVATRON.⁽⁵⁾

From the view point of machine scientists, who design the machines,

supervise their construction and commission the beams, they consider lattice non-linearity differently in hadron and lepton machines.

In hadron machines such as TEVATRON, SPS, the HERA proton ring, RHIC and LHC, radiation damping is not effective to restore the beam distribution in phase space so that they must consider the long-term dynamic aperture that is dominated by the beam-diffusion processes in phase space. These diffusion processes are brought about and enhanced by lattice non-linearity, which is often introduced by superconducting magnets, together with external modulations to the beams, such as synchrotron oscillation, tune ripple, the beam-beam effect, ground motion and so on. To make quantitative estimations of these diffusion processes solely by numerical simulations, since the present computer power is not sufficient the combined approaches of using experimental and computational studies have eagerly been carried out, especially at TEVATRON, SPS and IUCF.⁽⁶⁾

In lepton machines, such as (high-luminosity colliders) BEPC, CESR, TRISTAN, LEP, the HERA electron ring, DAΦNE, PEP-II, and KEKB as well as (high-brightness light sources) KEK-PF, NSLS, SSRL, ELETTRA, ALS, ESRF, APS, and SPring-8, since radiation damping and excitation dominate the beam distribution in phase space, machine scientists need not worry about long-term phenomena. The lattice non-linearity mainly results from the strong sextupoles for the chromaticity correction. Due to the short damping time, modern computers can provide sufficient computational power for calculating the dynamic aperture once sufficient information is provided concerning the machine parameters, including errors. In the following sections a series of beam experiments conducted at the TRISTAN MR are considered in order to show recent achievements in experimental techniques and observations of nonlinear dynamics in lepton machines.

BEAM EXPERIMENTS AT THE TRISTAN MR

A non-interleaved sextupole scheme⁽⁷⁾ has been proposed to make chromaticity corrections for high-luminosity circular colliders⁽⁸⁾ and very low-emittance light sources⁽⁹⁾ for the sake of the large dynamic aperture, even with strong sextupoles. In the non-interleaved sextupole scheme, sextupoles are to be arranged in pairs having the same strength. In each pair, sextupoles will be placed at the interval of the betatron phase (π) both horizontally and vertically, and will never be interleaved with other sextupoles. Nonlinear effects of the sextupoles will be canceled out automatically in each pair with this arrangement, so that the dynamic aperture can be kept large.

Although the non-interleaved sextupole scheme has shown excellent performances concerning the dynamic aperture in particle tracking using the SAD

code,⁽⁷⁾ it will be necessary to confirm the tracking results by beam experiments at real machines. To make a rigorous comparison between tracking and experimental results, quantitative knowledge concerning specific machine errors, e.g. the strength errors of quadrupoles, alignment errors of sextupoles and unexpected nonlinear fields, is essential. A series of beam experiments were conducted at the TRISTAN MR during the autumn of 1993 to measure the existing errors of the machine as well as its dynamic aperture with the non-interleaved sextupole scheme.

From the view point of beam dynamics, the purposes of the experiments can be summarized as follows:

- (1) To develop methods for beam-based measurements of machine errors, such as the strength errors of quadrupole magnets, alignment errors of sextupole magnets, and lattice non-linearity.
- (2) To check the reliability of the SAD code for computing the dynamic aperture, by comparing the measured dynamic aperture with the tracking results, including the effects of the measured machine errors.
- (3) To confirm the principle of the non-interleaved sextupole scheme, by measuring the amplitude dependence of a betatron tune that directly reflects the nature of the non-linearity of the lattice.

Beam-Based Measurement of Machine Errors

Imperfections in linear optics, such as beta-beating, will greatly reduce the dynamic aperture in cooperation with non-linear fields. In order to restore the dynamic aperture it is necessary to find specific distortions of the focusing force which cause linear-optics imperfections. To measure these focusing-force errors precisely in each individual magnet, the π -bump method has been developed. The principle of this method is explained in Fig. 1. In lepton storage rings, such as high-luminosity colliders and high-brightness light sources, the strength error of quadrupoles and the alignment error of sextupoles are often liable to such distortions of the focusing force. In the following are presented the π -bump method applied to measuring the strength error of quadrupoles and the alignment error of sextupoles in the TRISTAN MR together with the measured machine errors.

Strength Error Measurement of Quadrupole Magnets

In order to make a closed π -bump in normal cells of the TRISTAN MR, the kick-angle condition is simply $\theta_2 = \theta_1$ because steering magnets are located at the same interval as the period of the β -function. The FODO normal

cell was tuned to be 90° both horizontally and vertically for the sake of an effective arrangement of the non-interleaved sextupoles. Four quadrupoles and four bendings are included, as well as one or two sextupoles within a π -bump.

The sextupoles in a π -bump were switched off in order to avoid any effect of the sextupole field. Then, the π -bump amplitude was swept in order to check the linearity of the focusing force, which confirmed no significant non-linearity, except for a small effect induced by residual magnetization of the sextupoles.

From a measured orbit with a π -bump, the measured orbit without a π -bump was subtracted to obtain a leakage orbit free from any closed-orbit distortion. The obtained leakage orbit was fitted in a computer using two hypothetical steerings located at the target quadrupole and point-2. The fitted strength of a hypothetical steering at the target quadrupole was divided by the height of the π -bump at this point to obtain the strength error of the target quadrupole.

The height of the π -bump must be much larger in a target quadrupole than in the others, so that one can ignore the contribution from the others. This is also our case. When this condition is not satisfied, it must be analyzed by a simultaneous equation including many π -bumps. The strength error of quadrupoles in normal cells obtained by this method is shown in Fig. 2-(a).

For the insertion quadrupoles, the π -bump requires some more efforts. For each pair of steerings, one must prepare individual optics to produce a phase advance of π between them; the kick-angle condition should be $\theta_2 = \theta_1 \sqrt{\beta_1/\beta_2}$. In optics preparation, one must be careful not to use quadrupoles at a different excitation level from the nominal one, because the strength error usually depends on the excitation level. The obtained error of the insertion quadrupoles is shown in Fig. 2-(b).

Miss-Alignment Measurement of Sextupole Magnets

The principle of the π -bump method used to measure the miss-alignment of the sextupole for the horizontal and vertical directions is explained in Fig. 3 along with the experimental data taken at the TRISTAN MR. The miss-alignment of the sextupoles including monitor offsets was measured around the ring, as shown in Fig. 4.

To prove the effectiveness of the method, the orbit was adjusted to the measured center of the sextupoles of a certain family. The strength of the sextupoles was altered so as to shift the betatron tune if the orbit was not centered at the sextupoles. The observed tune change was much smaller after the orbit adjustment than before it.

Dynamic Aperture with Machine Errors⁽¹⁰⁾

A dynamic-aperture measurement was conducted for the horizontal, vertical and longitudinal directions. The longitudinal one was measured through the injection efficiency by shifting the injection phase to an rf phase, and also by sweeping the magnetic field of the ring; both gave the same result and agreed with a calculation by SAD. In the horizontal direction two working points of the test optics were examined by kicking the beam; both gave a remarkable agreement between the SAD calculation and the measurement, as shown in Fig. 5. On the other hand, a narrow physical aperture in the vertical direction was introduced by an accidental miss-alignment of a vacuum gate-valve and prevented a measurement of the vertical dynamic aperture of the test optics.

Measurement of the Lattice Non-linearity

The amplitude dependence of a betatron tune is a fundamental index of lattice non-linearity. The coherent oscillation of a kicked beam was used to measure the amplitude dependence of the betatron tune.

Precise Measurement of the Instantaneous Tune and Amplitude

In order to measure the amplitude dependence of a betatron tune in lepton storage rings, precise measurements of the tune and amplitude must be performed within a small number of turns because of oscillation damping by synchrotron radiation. The adopted process to do this is:

- (1) Accumulate position data of a kicked beam up to 16,000 turns with high accuracy and at a low beam current using a turn-by-turn monitor;⁽¹¹⁾
- (2) Take 256 turns of data and calculate the power spectrum by FFT applying the Hanning window;
- (3) Find 3 bins in the peak of the power spectrum and fit them with parabola in order to obtain the interpolated values of the tune and amplitude; and
- (4) Shift the data by 50 turns for the next step and repeat the procedure until the end of the data.

Head-Tail Effect and Nonlinear Filamentation

To avoid any coherent damping caused by the head-tail effect,⁽¹²⁾ the beam oscillation must be measured at a low current, as shown in Fig. 6.

Also, the amplitude dependence of a betatron tune causes oscillation damping through de-coherence among the particles' oscillation phases. This

phenomenon (often called the nonlinear filamentation) is suppressed when the beam motion is in the weak non-linearity or the damping rate (supplied by the radiation and the head-tail effect) is high, as shown in Fig. 7.

Amplitude Dependence of the Tune

The horizontal tune decay was measured in non-interleaved and interleaved sextupole schemes, as shown in Fig. 8. It was clearly demonstrated that the tune depends on the oscillation amplitude one order of magnitude less in the non-interleaved sextupole scheme than in the interleaved one, as expected from the SAD calculation. A successful suppression of the nonlinear effect by sextupoles on beam by the non-interleaved sextupole scheme has thus been proved.

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Figure 1: Schematic configuration of the π -bump method by which the focusing-force error is measured. Kicks are given at point-1 and point-2 under the condition $\theta_2 = \theta_1 \sqrt{\beta_1/\beta_2}$. The bump orbit should be locally closed when the (1,2) element of the transfer matrix from point-1 to point-2 is zero or, in other words, the betatron phase advance is π . A leakage orbit will arise around a ring if there exists a focusing-force error or a kick-angle error. These two kinds of errors contribute to a leakage orbit with phase difference of 90° , and can be evaluated individually from the measured leakage orbit.

Figure 2: (a) Measured strength error of normal cell quadrupoles. A systematic error of the QF is produced by an over-correction of the neighboring magnet's effect. (b) Measured strength error of the insertion quadrupoles. Four QC1's, whose errors are especially large, are excited at a much lower level in this test optics than in the daily used optics.

Figure 3: By sweeping the amplitude of the horizontal π -bump in a target sextupole, the deflection angles at the sextupole were calculated for both the horizontal and vertical directions from the measured leakage orbit. The horizontal and vertical deflection angles (θ_h and θ_v , respectively) are given by $\theta_h = \frac{1}{2}b_2\delta x^2 + b_2\delta x\Delta X$ and $\theta_v = b_2\delta x\Delta Y$. Where b_2 , δx , ΔX , and ΔY are the normalized strength of the sextupole magnet, horizontal beam position, horizontal miss-alignment of sextupole, and vertical miss-alignment of the sextupole, respectively. The peak (or bottom) position of the θ_h curve gives the horizontal center of the sextupole magnet and the gradient of the θ_v line gives the vertical off centering of the sextupole.

Figure 4: Measured miss-alignment of the sextupole magnets.

Figure 5: Comparison of the dynamic aperture between the SAD calculation and the measurement at the TRISTAN MR in the non-interleaved sextupole optics.

Figure 6: Dependence of the horizontal oscillation decay on the bunch current. The beam was kicked horizontally at the same initial amplitude and various bunch currents in the interleaved sextupole optics. The head-tail effect increases the damping rate in proportion to the bunch current. At the smallest current, the oscillation damps at the radiation-damping rate.

Figure 7: (a) Appearance of nonlinear filamentation in the vertical oscillation decay. The beam of the bunch current (0.03mA) was kicked vertically at various initial amplitudes in the non-interleaved sextupole optics. Nonlinear filamentation expressed by the parabolic curve arises from a strong kick. (b) Suppression of nonlinear filamentation in the vertical oscillation decay. A beam having various bunch currents was kicked vertically at the same initial amplitude in non-interleaved sextupole optics. Nonlinear filamentation is suppressed by the head-tail damping effect at higher bunch currents.

Figure 8: Decay curves of the horizontal tune show how differently the tune depends on the amplitude in the interleaved and non-interleaved sextupole optics. The 50Hz ripple modulates the tune in the both optics. (a) In the interleaved sextupole optics, the beam of bunch current (0.018mA) was horizontally kicked into 2.7mm, 3.6mm and 5mm. (b) In the non-interleaved sextupole optics, a beam having a bunch current of 0.023mA was horizontally kicked into 4.5mm, 9.2mm and 13mm.