EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CERN - SL Division

SL/Note 95-17 (AP)

EXPERIMENTAL TECHNIQUES AND OBSERVATIONS
WORKING GROUP REPORT

W. Scandale

Abstract. Experiments on single-particle non-linear dynamics are conducted since several years in existing accelerators. The aim is to observe the practical implications on beam stability of the unavoidable non-linear field present in modern lepton or hadron accelerators. Appropriate experimental devices and techniques have been invented and are used in various High Energy Physics Laboratories in the world.

Presented at the Workshop on Non-Linear Dynamics in Particle
Accelerators: Theory and Experiments,
Arcidosso, Italy, September 4-9, 1994

Geneva, Switzerland
February 1995

Experimental Techniques and Observations Working Group Report

W. Scandale

CERN, CH-1211 Geneva 23, Switzerland

Abstract. Experiments on single-particle non-linear dynamics are conducted since several years in existing accelerators. The aim is to observe the practical implications on beam stability of the unavoidable non-linear field present in modern lepton or hadron accelerators. Appropriate experimental devices and techniques have been invented and are used in various High Energy Physics Laboratories in the world.

LIST OF THE PARTICIPANTS

Jeff Corbet (SLAC), Max Cornacchia (SLAC), Fatme Iazzourene (Sincrotrone Trieste), Sumumu Kamada (KEK), Martin Lee (SLAC), Mauro Migliorati (Università di Roma), Claudio Pellegrini (UCLA), Modesto Pusterla (Università di Padova), Lenny Rivkin (SIN), David Robin (LBL), Francesco Ruggiero (CERN), James Safranek (BNL), Walter Scandale (CERN), Lee Teng (ANL), Phang Tran (SLAC), Al Temnykh (CORNELL), Ezio Todesco (Università di Bologna), Jacques Laskar (Bureau des Longitudes, Paris).

INTRODUCTION

Despite the recent progress in understanding non-linear dynamics and in performing sophisticated numerical simulations, our ability to predict the dynamic aperture in particle accelerators is quite limited. The theoretical methods available are not yet rigorously mastered, and the models for computer simulations are in general unable to include all the relevant phenomena characterising the motion in particle accelerators. Dedicated experiments with existing accelerators are therefore considered a useful way to extend our knowledge on the phenomenological aspects of the particle motion in presence of non-linearities, and to reduce the gap between computer models or analytical understanding and reality.

The motivations for non-linear dynamics experiments have two facets. Observations performed under controlled conditions are of a paramount importance to investigate in detail the behaviour of existing machines. This is first to the benefit of their operational performances, but also to that of other already existing accelerators of the same class. On the other hand, specific experiments can be devised to check the validity of theoretical calculations or the predictivity of numerical simulations. The hope is that, in comparing experimental results with theoretical or numerical predictions, it is possible to define suitable criteria or appropriate procedures for beam stability, that, in turn, can be used for safe predictions at design stage in new accelerator projects.

Nowadays and since at least a decade, the studies of non-linear single-particle beam dynamics are devoted to two main fields: the large superconducting hadron colliders, dominated by unintentional imperfections of the magnetic field-shape, and the low-emittance lepton accelerators, governed by chromatic aberration correctors. The discussions of the Working Group were mostly devoted to the latter field, the former one was, instead, more deeply treated in the Theoretical and Computational Techniques Working Group .

ASPECTS OF NON-LINEAR DYNAMICS EXPERIMENTS

Several new accelerator projects are proposed, approved, or under construction, all over the world. Most of them are expected to encounter severe performance limitations due to various non-linear phenomena. Dedicated experiments on existing machines can provide fundamental information on these limiting mechanisms and on possible strategies to overcome them. An non-exhaustive overview of the present situation is synthetically shown in Table 1.

Table 1. Experiments in non-linear dynamics: where and why ?

	Hadron accelerators	Lepton accelerators
Machines in preparation	LHC, RHIC	particle factories: DAΦNE, PEP II, KEKB, ... light sources: APS, Spring-8, ...
Main source of non-linearity	field-shape imperfections in the superconducting magnets	sextupole magnets for chromaticity correction.
Matter of interest	long-term dynamic aperture, diffusion mechanisms, effect of power supply ripple, beam-beam phenomena, collective effects	short-term dynamic aperture, tolerance on machine errors, beam-beam phenomena, collective effects
Suitable machines for experiments	SPS, TEVATRON, IUCF, HERA-p,...	TRISTAN, CERS, LEP, HERA-e, ... ESRF, ALS, ELETTRA, KEK-PF, NSLS, SSRL, ALADDIN, ...

However, extracting information in full detail on non-linear dynamics from working accelerators may be extremely difficult because of the complexity inherent in their modes of operation. Repeated experimental sessions may be needed to collect representative samples of data for different machine parameters, with stable operational conditions. In addition, the orbit functions and the linear machine parameters have to be carefully investigated, in order to estimate the residual imperfections, like bad positioning of the quadrupoles, magnetic field and gradient mismatch, residual linear coupling and so on. The procedures to obtain all this information is, often, time consuming, therefore, in conflict with the operational schedule of the accelerator.

In the various accelerator facilities, the particle motion follows different time-scales. In lepton accelerators, the beam dynamics is governed by the radiative

phenomena, that induce damping with typical duration of the order of the msec. In hadron storage rings, instead, the radiation damping is negligible up to very high energies. The perturbations on the particle orbits are, therefore, cumulated for the entire operational cycle, that may last several hours. Finally, low-energy hadron colliders with electron-cooling devices are a case of a special interest: they can produce pencil beams of very low emittance, particularly suited to explore the phase-space, with typical cooling time ranging from a few seconds to a few minutes.

Observations of the phase-space portrait, of the tune-shift with the amplitude and the momentum, and the experimental evidence of isolated single-resonances, can be made in short time-scales, of the order of a few msec, in all kind of accelerators.

The measurement of the dynamic aperture and its comparison with tracking simulations, instead, have at least two different regimes of interest, expressed in terms of the number of stable revolutions along the ring.

The short-term dynamic aperture requires confinement for 10^3 to 10^4 revolutions. This is a situation mostly concerning the lepton colliders, where slow loss mechanisms are in competition with the radiation damping. In hadron collider, this regime is relevant for transient phenomena, such as the injection process, or for some perturbative beam observation, like, for instance, the measurement of the chromaticity or the exploration of the phase-space parameters as a function of the amplitude.

The long-term dynamic aperture instead concerns steady-state regimes lasting 10^7 to 10^9 revolutions, like the injection or the collision plateaux in the hadron colliders. Its investigation imply the understanding of the slow diffusion mechanisms due to higher-order resonances, that, in turn, is strongly influenced by the residual ripple in the main power supplies of the guiding and focusing magnets.

Experimental procedures are available to explore the non-linear features of the particle motion in an accelerator. To probe the structure of the phase space, the circulating beam is, in general, deflected at large amplitudes. This is obtained either by a single-pass large deflection, or by repetitive small-amplitude coherent kicks. The consequent distribution of charges is different for lepton or hadron beams, due to the different radiation regime. However the same kind of observations can be made in both cases, with various instruments: current transformers record lifetime, Schottky noise detectors give tune and tune-spread, flying wires provide transverse profile, and orthogonal pairs of position monitors are able to produce a phase-space portrait. Sinusoidal tune modulations can be added to enhance the effect on the beam stability of the unavoidable ripples in power supplies.

DYNAMIC APERTURE IN LARGE LEPTON ACCELERATORS

It is not always easy to predict the non-linear behaviour of the leptons in large synchrotrons, although reliable estimates of the dynamic aperture and of the detuning functions can, in principle, be obtained with 10^3 to 10^4 revolutions only. The source of the ambiguity can be either in the inadequacy of the simulation models, or in the multiplicity of the experimental procedures.

Four different protocols can be followed to measure the dynamic aperture, based on the observation of the following quantities:

- beam lifetime without beam excitation for different emittances and/or sextupole strengths;
- current loss at injection for different injection conditions;
- current loss after a single-turn deflection of increasing amplitude;
- beam lifetime for resonant excitation of increasing amplitude, for different excitation frequencies.

In the last two cases, it is appropriate to make precise calibrations of the effect of the single kick or of the resonant perturbation, by measuring the charge distribution either with flying wires or with sets of collimators.

Computer simulations required to interpret the experimental results can be made with different levels of refinement. Direct multi-particle simulations, that include radiation effects, can provide the most realistic estimate of the beam lifetime, however they are rather CPU-time consuming. Suppressing the radiation effects helps to speed-up the numerical computations, and gives still reasonable estimates of the dynamic aperture, provided that the saw-tooth dependence of the energy along the azimuth of the accelerator, known as Bassetti effect, is taken into account. Simulations should include beam excitation by single kick or resonant excitation to improve their predictivity.

The difficulties to estimate the dynamic aperture of LEP have been reported by F. Ruggiero (1).

- Recent measurements, based on single-kick beam excitation, and short-term simulations of the dynamic aperture, including radiation damping, are in a rather good agreement. Instead, measurements based on resonant excitation are in a good mutual agreement, but indicate a dynamic aperture smaller by about a factor of two with respect to the value obtained with single-kick beam excitation.
- The measured values of the horizontal and the vertical chromaticity do not follow theoretical estimates, unless an appropriate amount of sextupolar field-shape imperfection is assumed in the guiding dipoles, which slightly differs from that computed from direct magnetic measurements.

S. Kamada (2) reported on the investigations of the non-linear beam-dynamics in KEK.

- The actual values of some linear parameters, like the deviation of the quadrupole strengths and the mechanical offset of the chromatic sextupoles, have been measured, using the well known technique of performing local beam bumps and observing the residual orbit leakage. The statistical distribution of these imperfections has been estimated and incorporated in the non-linear model used for computer tracking simulations. After that, the computed values of the detuning with amplitude has been found to be in good agreement with measurements.
- In the nominal operational conditions, the dynamic aperture is well above the physical limitations and therefore cannot be compared with simulations. Dedicated experimental sessions have been devoted to this investigation, during which the dynamic aperture was intentionally reduced by introducing non-interleaved schemes for chromatic corrections or non optimised values of the working tunes. The results of these measurements were in good agreement with the computed values of the dynamic aperture.
- The instantaneous tune is measured with a turn-by-turn position monitor, operating at small current. The information on the transverse beam position is digitised and stored over several thousand revolutions and then used to produce Fast Fourier Transform coefficients. A set of 256 points is used to

compute the betatron frequency, with a resolution of $2 \cdot 10^{-3}$, that can be considerably improved with a Hanning windowing of the data and a parabolic fit of the FFT coefficients on the three bins at peak. The temporal evolution of the tune is finally obtained by successively applying the FFT analysis to sets of 256 points shifted by 50 turns each. Superposed to the exponential decay due to radiation damping, a tune modulation at 50 Hz due to ripple, is, in general, well visible. In addition, the measured value of the initial detuning is always in an excellent agreement with numerical simulations.

Two remarks emerge from the previous discussion, that are relevant for the experimental investigations in any accelerator and in particular in the large lepton colliders:

- It is of paramount importance to base the interpretation of the experimental results on a solid knowledge of the linear parameters of the accelerator and on a realistic estimate of the linear imperfections.
- In addition to the standard instrumentation based on position, current and loss monitors, a tool is needed for the precise measurement of the instantaneous tune, having a response-time fast enough to be in competition with the radiation damping time, the non-linear filamentation, and the head-tail damping time.

EVIDENCE OF ISOLATED SINGLE-RESONANCES

The evidence of isolated single-resonances is a well-known phenomenon, that has been deeply investigated in particle accelerators, both from the analytical and the experimental point of view, and that can be operationally exploited, for instance, to produce the resonant slow extraction of the circulating particles.

In our discussions, emphasis was given to description of some experimental devices by which it is possible to explore the working diagram, and reveal non-linear resonances.

D. Robin (3) reported on the observation of non-linear resonances induced in ALS by a super symmetry breaking, due to the intentional mistuning of one lattice quadrupole. Small gradient variations of less than $\pm 6\%$ are sufficient to excite structural resonances, that are not allowed in the nominal 12-fold symmetric lattice.

The width of the excited resonance can be measured by a simple experimental set-up, fully computerised, based on the fast measurement of the beam lifetime. The leptons with resonant tunes hit a collimator well inside the mechanical aperture and produce secondary losses that can be detected by a Geiger-Muller (GM) counter, located downstream of the collimator. A typical measurement is made in repeated steps, lasting two seconds each, during which the tunes are varied in the vicinity of the resonant value, and the circulating current and the number of counts detected by the GM counter in one second interval are measured and used to deduce a value proportional to the beam lifetime. It was shown, for instance, that :

- with nominal quadrupole gradients, the resonances of order three and five have a comparable width and amplitude;
- with a gradient error of 1% the structural resonance of order three is already well enhanced;
- with a gradient error of 6% the entire beam intensity is lost when the third resonance $3Q_x=43$ is crossed, whilst the resonance $5Q_x=72$ is practically unchanged.

A. Temnykh (4) discussed the technique used at CESR to observe the tune diagram. In a computer assisted system, the vertical beam size is detected by a one dimensional string of Charge Coupled Devices, whilst the quadrupole gradients are varied in steps. Since the crossing of a resonance produces an increase of the beam size, it is easy to produce 3-D graphics of the working space, that contain the resonance lines experimentally observed. As an example, the working diagram was observed in collision mode with and without the pretzel orbit distortion. In this way resonances induced by the off-axis crossing of the chromatic sextupoles were made evident.

It is nowadays quite common to install fast and reliable detectors to observe the non-linear resonances in particle accelerators. This is particularly easy in a lepton collider, in which the beam is more tolerant to external perturbations, and less prone to losses during resonance traversal. The use of these detectors can be very beneficial

- to improve the beam stability during the normal operation;
- to assess experimentally the validity of the non-linear model used in computer simulations.

OBSERVATION OF THE PHASE-SPACE PORTRAIT

In particle accelerators, the intersections of 6-D trajectories with the surface of the phase space characterised by a constant value of the energy, computed at the times $t = k \cdot T$, where T is the revolution period, provide the Poincaré map of the transverse motion at a given azimuthal position.

In tracking simulations it is easy to produce Poincaré maps, since, each turn, the six phase space coordinates at a given azimuth are simultaneously available.

Experimental methods to determine Poincaré maps in particle accelerators have been proposed by P. Morton at Slac in the early Eighties and are now commonly used in several laboratories.

A pair of beam position monitors, spaced in phase by 90° , can provide a turn-by-turn signal, from which one can construct projections in one phase-plane of the Poincaré surface of section. With three pairs of pick-ups, one horizontal, one vertical, and one longitudinal, it is possible to obtain the three main projections of the Poincaré map.

L. Teng reported one aspect of the ALS experiment on Aladdin, in which the phase-space portrait was measured to investigate the diffusion process between the central stable area and the surrounding resonant islands (5). The third order resonance was strongly excited by mistuning the chromaticity sextupoles. The three islands were initially populated by a single kick and the phase space portrait observed for several minutes. For a few turns, the particles were mostly moving towards the three stable fixed points. In the following minutes, the electrons were diffusing through the separatrices, due to the simultaneous effect of radiation damping and quantum noise. After about 10 minutes, the equilibrium was reached. Statistically the same amount of particles were jumping in and out of the stable area, therefore, the position of the centre of gravity of the beam, as seen by the pick-ups, was collapsing towards the origin of the phase space. Predictions, obtained with computer tracking simulation, and with analytical considerations as well, were in an excellent agreement with observations.

P. Tran and M. Lee presented the plans for an experiment to be performed at Spear, the scope of which is to observe the 6-D phase-space with three pairs of

pick-ups (6). The motivation of this study is related to the investigation of the performances of a special lattice suited for very short electron bunches. A vanishing value of the momentum compaction is required, and the dynamic aperture is expected to become too small. The hope is that, by inspecting the 6-D phase space portraits, one can construct experimentally the linear and the non-linear components of the one-turn map, and use this information to develop an algorithm to control the non-linearities of the accelerator. Preliminary results of the pick-up signals were presented. The sensitivity, the linearity and the reproducibility of the position monitor response have been identified as key issues of the experiment.

J. Safranek, in discussing the linear modelling of the NSLS at BNL (7), pointed out the difficulty to push the sensitivity of the beam position monitors towards the range of a few microns. He also emphasised that high quality measurements of the beam positions require a perfect control of the non-linear distortions due to the electronics or the mechanical design of the detector, and a large rejection of all type of noise. The present state of the art, allowed him to detect orbit positions with an uncertainty of the order of 2 to 3 microns.

EVALUATION OF THE BETATRON TUNE

The analysis of the tune diagram is an outstanding method to investigate the non-linear beam dynamics. In correlating the particle trajectories in the time domain with the tune footprints in the frequency domain one can identify:

- the location and the strength of the non-linear resonances,
- stability or instability of a given resonance,
- phase locking mechanism,
- the interplay between resonances, dynamic aperture, and detuning.

The experimental value of the tune is, in general, obtained by executing the FFT of the turn-by-turn beam position, measured for a fixed number of revolutions. The analytical value of the tune can be obtained either with the classical Hamiltonian approach or using the perturbation theory of the one-turn maps based, for instance, on normal forms. In numerical simulations, the tune can be estimated with FFT algorithms, but also by computing the average phase advance per turn, or some other sophisticated algorithm, like the one proposed by J. Laskar (8), based on a refined Fourier analysis of quasi-periodic trajectories.

E. Todesco presented preliminary considerations to estimate the precision of tune computation as a function of the number of turns N , in the available numerical methods:

- the FFT give an uncertainty proportional to $1/N$
- with the average phase advance per turn, the indetermination is proportional to $|x|/N$, where x is the oscillation amplitude;
- the method of Laskar is expected to be extremely accurate: the conjecture was expressed that its error can be proportional to $1/N^2$.

J. Laskar discussed how the frequency analysis method can be applied to the study of the stability of the solar system, where it permitted an accurate estimate of the size of the chaotic zones. He also applied it to study the global dynamics of a 4-D symplectic map approximating a particle accelerator. The frequency analysis can be used to produce frequency footprints at two different times. From them, the maximum speed of transport in the frequency space can be computed for each initial condition, and used to evaluate the regularity of the motion.

CONCLUSION

In the past, experimental investigations have been an essential tool to increase our phenomenological understanding of non-linear phenomena in particle accelerators, and to improve our confidence in their performance. Our progress were mostly driven by the necessity of solving specific problems in a given machine, rather than by a general concern of the non-linear dynamics. This seems to me a very productive manner to continue our studies also in the future, having in mind a wide spectrum of quite ambitious aims, like, for instance:

- improving the operational performances of existing accelerators,
- understanding their limiting mechanisms,
- providing realistic models that explain the observed non-linear effects, and that are compatible with the results of known magnetic measurements,
- identifying heuristic methods for a predictive guidance in the design of future accelerators.

This program of study is very demanding in terms of accelerator resources and manpower. It is essential to have:

- a flexible and accurate beam instrumentation,
- a perfect knowledge of the linear parameters of the accelerator,
- a schedule of the accelerator time with sufficiently long and frequent experimental runs for data taking with stable operational conditions.

Discussions and exchange of experience, as in this workshop, are therefore of a great importance.

ACKNOWLEDGEMENT

I wish to gratefully acknowledge the effort of the local organising committee, and in particular that of Melinda Laraneta, Silvia Giromini and Gianfranco Nanni.

The warm hospitality of the Mayor and the population of the Town of Arcidosso made possible a very pleasant and efficient progress of the workshop.

REFERENCES

- (1) F. Ruggiero, *these proceedings*
- (2) S. Kamada, *these proceedings*
Y. Funakoshi (for the Dynamic Aperture Issue Working Group), *KEK Preprint 94-72, submitted to EPAC 94*
- (3) D. Robin, *these proceedings*
- (4) A. Temnykh, *these proceedings*
- (5) J. Liu et al, *Particle Diffusion from Resonance Island in Aladdin at SRC, 1993 PAC at Washington D.C. Vol. 1, p 285 (1993)*
- (6) P. Tran et al, *SLAC PUB 95-6720*
- (7) J. Safranek et M. Lee, *EPAC94, p. 1027. London, 27 June-1 July, 1994*
- (8) H. S. Dumas, and J. Laskar, *Phys. Rev. Lett. Vol. 70, No 20, p. 2975 (1993)*

DEMANDE DE REPRODUCTION SL

A : B. Charvet / Division MT

Date:

De : J. Thomashausen / Division SL

Signature :

20 fev 95
Juliette

Veillez faire 60 copies du document ci-joint
et RENVoyer cette fiche avec l'original .

Nombre de copies

☐ **Abstract** de rapport, à envoyer à l'adressage *

Fait, le _____

☐ **Rapport de division**, à envoyer à l'adressage *

Fait, le _____

☒ **A envoyer au secrétariat**

Fait, le 20/2/95

☒ **20 exemplaires aux "Archives_SL"**

Fait, le 11

☐ **Instructions particulières :**

* Demande d'Impression d'Adresses ci-joint.

merc.