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Understanding Nonlinear Effects and Losses*†

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ABSTRACT

With the planned construction of a large hadron collider (LHC) and a major upgrade of LEP (LEP–II) at CERN, a Φ–factory at Frascatti, and B–factories at SLAC (PEP–II) and KEK (KEK–B), we are now entering new energy and intensity regimes in both electron and proton circular colliders. Understanding and accurately estimating dynamic apertures and particle loss rates under both injection and colliding beam condi-tions is of primary importance. This paper summarizes discussions on Understanding Nonlinear Effects and Losses that took place in Working Group Three at the September 1994 Conference on Nonlinear Dynamics in Particle Accelerators at Arcidosso, Italy. Questions addressed were: "What do simulations indicate as the underlying causes of particle loss?" and "Do experiments agree with simulations—and if not, why not?" Special attention was given to a discrepancy between dynamic aperture measurements and theoretical predictions at HERA.

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* Working Group Three Summary.

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INTRODUCTION

For both electron and proton rings, there is no simple theory that can explain quantitatively where the dynamic aperture will lie, or what the particle loss rates will be. The best that currently can be hoped for is a qualitative understanding of underlying mechanisms, coupled with simulations that quantitatively agree with experiment.

Given these limitations, the dynamic aperture of electron rings is well understood; however, the beam-beam loss rates are not quantitatively predictable. Because of damping, resonance effects must be responsible for determining dynamic apertures and particle loss rates. Recent experiments indicate good agreement between dynamic aperture simulation and measurement. Advances in tracking with maps have improved the lattice design process, providing the designer with a global tune-plane view of the lattice dynamic aperture. New codes for beam-beam halo simulations have clarified underlying mechanisms. Experiments to confirm beam-beam simulations are in progress, but are far from yielding quantitative agreement.

The situation with proton rings is less satisfactory. Dynamic apertures are difficult to simulate; diffusion, modulation, and noise are clearly important. At HERA, there is a factor of two disagreement between simulation and experiments; while for a recent experiment at SPS, simulations and experiment appear to agree.

We expand upon the current situation with electrons, and then move on to protons, ending with a summary of the working group's discussion of the possible causes of the disagreement between dynamic aperture measurements and simulations at HERA.

ELECTRON RINGS

Importance of Resonances

Because of significant damping in electron rings, particle loss must occur in a fraction of a damping time, which is typically a few thousand turns. This means that the loss mechanism must be due to resonances; no other mechanisms are known which dramatically change particle amplitudes in so few turns. There is no shortage of resonances in the tune plane when synchrotron sidebands are considered along with geometric resonances. The important geometric resonances are usually at the integer and half integer, and along lines driven by sextupole and octupole aberrations. Particle loss requires being on (or crossing) a resonance that is strong enough to cause particle loss. The quantities of primary concern are thus: (i) the working tune, (ii) tune shift with amplitude and tune shift with energy terms, and (iii) resonance strengths. Strong chromatic terms linear in transverse variables can lead to significant sidebands on geometric resonances.

It is well known that tune shift with amplitude terms can be too small, as well as too large. When the tune shift with amplitude is too small, resonances have very large island widths, facilitating particle loss. It becomes quickly apparent that although there is a good qualitative understanding of the particle loss mechanism, there is still not a good quantitative understanding—we must rely on hours of computer simulations to acquire quantitative information. This is cumbersome, since we want to understand lattice behavior for a broad range of working tunes.

A fast map tracking method [nPB tracking (1)] reported at this conference has assisted the PEP–II design process. Dynamic apertures for one working point are determined in 30 seconds on current RISC workstations (compared to 2 hours for element-by-element tracking), making it possible in an overnight run to study lattice behavior throughout a large area of the tune plane. A broad range of resonant features are evident, and lattice design can proceed efficiently and intelligently. This method allows modification of the resonance or tune shift with amplitude strengths in the map, and observation of the impact before the more lengthy lattice modification procedure.

What's New

The high-intensity high-luminosity Φ and B factories use low-beta insertions to improve single-bunch luminosity, and they have two distinct beam paths through the interaction region to facilitate multibunch operation. This leads to a number of new and important effects: (i) large chromatic compensation requirements, (ii) kinematic terms in the Hamiltonian arising from large angles at the IP, (iii) important quadrupole fringe effects from large β functions at the insertion quadrupoles, (iv) important feed down terms from beam lines not centered in optical elements, and (v) parasitic beam-beam crossings, as well as head-on beam-beam effects (2). The kinematic terms and quadrupole fringes produce octupole-like aberrations, and the quadrupole soft fringe can contribute important dodecapole terms. Depending on design details, these octupole terms can dramatically change tune shift with amplitude terms. If permanent magnet quadrupoles are used, the inherent large high-order systematic aberrations can become significant as a result of feed down.

These new rings employ a variety of innovative chromatic correction techniques: (i) noninterleaved sextupoles in arcs (3), (ii) local chromatic correction schemes that resemble linear collider final focus systems (4), and (iii) semilocal chromatic correction schemes employing β-bumps within arc modules (5). Experiments at TRISTAN have verified that the dynamic apertures of the noninterleaved sextupole schemes agree with theoretical predictions (6). Octupole families have been proposed for PEP–II to control tune-shift with amplitude terms (7).

An interesting, perhaps counter-intuitive, reduction in the dynamic aperture resulting from the very large damping present in LEP-II was reported (8). As particles move to larger transverse amplitude, they radiate more strongly, changing the position of the longitudinal fixed-point. In this way, the particle also acquires a large longitudinal amplitude, which leads to a decrease of the dynamic aperture.

Beam–Beam Tails

Two programs are now able to simulate the halos of the beam-beam interaction (9). These programs have confirmed the resonance streaming model proposed by Tennyson (10) and the resulting phase-space convection (11). New features, such as crossed-resonance trapping, have also been observed (12). Although there is not enough control on experimental conditions to prove or disprove the predictions of these programs (13), they do agree with brute-force tracking (which takes 2500 times more computer time). Thus, it seems that they can at least be relied on for qualitative information. The variation in beam-beam tails under the change of several parameters ($d\beta/d\delta$ at IP, collision off-sets, tune shift with amplitude, working tunes, etc.) has been a guide to PEP–II lattice design and tolerance specifications. It has also been shown that the presence of lattice resonances enhances resonance streaming (12).

PROTON RINGS

Dynamic Aperture

The dynamic aperture for proton rings is a more subtle phenomena than electron rings. There is no dominant damping and, to assure orbit stability for 10^8 turns, particles must be tracked for some fraction of that number. There have been many efforts to reduce this fraction using early indicators of instability [presence of diffusion, Lyapunov coefficients (14)], even though it still seems that the most widely accepted standard is a simple "survival" plot, which indicates the number of turns a particle survives versus initial amplitude. In addition to the importance of resonances, it has been established that diffusion, noise, and modulation of any lattice parameter can all have a significant impact on dynamic aperture.

A clarification of the underlying process has been given by Gallucio and Schmidt (15). They have shown how particles migrate in tune space until they find a resonance line, which can be of high order, and are then lost quite rapidly. The survival plots which accompany this study show a box-like structure, which suggests that at different amplitudes there is a piece-wise varying time required to diffuse to nearby resonances. J. Laskar (16) has presented a method at this conference for fast identification of particle tunes, which he then uses to quantify tune migration and predict orbit instability.

It is interesting in this connection that Yan (17) was able to show by symplectic map tracking using a mixed variable generator, that for the SSC lattice, only terms in the one-turn generator through order five were needed to get agreement with element-by-element tracking. This indicates that at least for the SSC, the high-order resonance lines are driven by multiturn feed-up from low-order resonances of the one-turn map.

The presence of diffusion has been confirmed in experiments at HERA (18). F. Zimmermann has done an exhaustive study of diffusion mechanisms that may be present (19). These include chaotic (Arnold) diffusion from several resonances; diffusion from phase space distortions, and its enhancement by resonance streaming; modulational diffusion; and "sweeping" diffusion. None of these diffusion mechanisms yields a diffusion coefficient that would remotely begin to explain the dynamic aperture measured at HERA. Simulation results and measurement at HERA indicates roughly a factor of 2 difference between the onset of chaotic motion and the measured dynamic aperture (20).

Looking for physics that is not included in these simulations has led to a study of sources of modulation at HERA. Candidates include power supply ripple, ground motion, vacuum pump vibrations, and chromatic effects. The modulation of the beam can be quite nicely observed by looking at the modulation of tail particle densities as a detector is inserted into the beam. A rich modulation spectrum is observed.

This has led O. Bruening et al. (21) to modify the modulation spectrum to see if it has an impact on dynamic aperture. His first experiment concentrated on a 50 Hz signal, and he found it was possible to reduce the measured strength of this modulation. The dynamic aperture did change: unfortunately it became larger rather than smaller. Since the modulation was being observed only at one phase, the sign of the change could perhaps be forgiven, and this result may be a positive indicator of the importance of modulation. Further studies are necessary.

On the other hand, Fischer et al. (22) reported experiments done on the SPS at CERN that indicate an agreement between observation and experiment. For purposes of his experiment, lattice nonlinearities were enhanced by introducing additional sextupoles, and modulation was also introduced.

Beam–Beam

In addition to dynamic aperture experiments, observations were made of lifetimes and emittance growth during colliding beam operations at HERA. The beam lifetime decreased from more than 1000 hours (with an accompanying emittance growth rate of less than 0.5 mm-mrad per hour) to a lifetime with beam-beam collision of about 200 hours (with an emittance growth rate ranging from π to 15 π mm-mrad/hour). It was reported that these lifetimes and growth rates can be attributed to noise and modulations of the electron beam in the beam-beam collision, and that growth rates were reduced as the electron beam conditions were improved.

HERA Factor of Two?

The disagreement of the measured and simulated dynamic aperture at HERA is a cause of concern to the LHC design team. By using survival plots up to 5×10^5 turns and using Lyapunov coefficients as an indicator of chaos, the LHC design lattice has a simulated dynamic aperture of 6 σ. If the tune is modulated by one part in 10^4, the dynamic aperture decreases by about 10%, to 5.4 σ. If these estimates are optimistic by a factor of two, resultant machine operation at a dynamic aperture of 2.7 σ would be quite uncomfortable.

Working group three had an animated discussion of the probable cause of the discrepancy at HERA. Opinions varied from a belief that there is something wrong with the measurements, to a belief that there is something missing or wrong in the model. The large majority favored something missing or wrong in the model. The possibilities for errors or omissions in the model included: (i) wrong fields, (ii) more noise, (iii) more modulation, or (iv) some unknown physics. Discussion of item (i) centered on the strength used for the random sextupole in the ring. It is known that the sextupole strength does change with time during each injection cycle. To explain the dynamic aperture measurement, it would have had to change by a factor between 1.5 and 2 larger than present estimates (see note 20). There was also an expressed belief that there could well be unknown nonlinear fields present, such as sextupoles with reversed leads (although the systematic sextupole is quite small, and could not account for the observed discrepancy).

G. Turchetti presented a paper at this conference addressing the inclusion of noise into accelerator modeling (23); he suspected item (ii) of being the culprit. Item (iii) is being pursued vigorously by O. Bruening. Item (iv) is always possible, but candidates are scarce. F. Willecke suggested that perhaps anharmonic modulation, which would have a very rich modulation spectrum and would perhaps need to be modeled directly, could play a role that was distinct from the harmonic modulation studied so far. Of course, the possibility cannot be excluded that a little of all of these effects add up to the observed results.

SUMMARY

The observed dynamic aperture of electron rings agrees well with simulations. Resonance effects are responsible for determining dynamic apertures. Recent advances in tracking with maps provide the designer with a global tune-plane view of the lattice dynamic aperture. New codes for simulating beam-beam halos are beginning to clarify underlying particle-loss mechanisms, but still do not quantitatively agree with experiments.

Reasons for the possible HERA discrepancy were presented and evaluated. Dynamic apertures for proton rings are more difficult to simulate—diffusion, modulation and noise play an important role in determining apertures. At the time of the workshop, there was a factor of 2 disagreement between simulation and experiments at HERA; however, recent experiments shows better agreement (20). In a recent experiment at SPS, simulations and experiment also appear to agree.

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20. Note added in proof. Zimmermann, F., and Willeke, F., private communication: After the Arcidosso Conference, dynamic aperture measurements were repeated at HERA. Experiment and theory are in better agreement. Experiments now give 1.5–2.3 π mm-mr, and tracking gives 2.5–3.3 π mm-mr. Apparently, the $b_{3,rms}$ (arising from b_3 change on each injection cycle) was larger than previously realized. See also Willeke, F., "Comparison of dynamic aperture calculations with experiments," TAG2, 1995 Part. Accel. Conf. (PAC 95).

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