Review of Beam Dynamics Experiments and Issues in Large Colliders

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Abstract

The nonlinear dynamics of transverse particle oscillations are being studied experimentally with several large synchrotrons. In the FNAL Tevatron and the CERN SpS, sextupole magnets are used as the sources of nonlinear forces. Studies are also being performed in the FNAL Main Ring at its injection energy, an inherently nonlinear environment. Here, we present a brief review of these studies. We conclude with a discussion of field quality and aperture issues in large hadron colliders.

1 Introduction

The experiments described in this report are motivated by the need to refine the aperture and field quality criteria of large hadron accelerators. It is difficult to calculate the dynamic aperture at all, and it is at present outside the bounds of possibility to carry out extensive parametric studies with the dynamic aperture as the measure of the region of interest. Though the limits of stability are hard to determine, deviation from linear behavior is much easier to calculate. The magnetic field quality specification used in the SSC Conceptual Design Report is based on the imposition of bounds to the departure from linear behavior in the oscillation of single particles about their closed orbits.

If the betatron oscillations of a particle in a synchrotron are linear, then the oscillation amplitude will be a constant of the motion. If there is no coupling between the two transverse degrees of freedom, the projections of the amplitude on the horizontal and vertical planes will each be an invariant. A turn-by-turn plot of the vertical projection versus the horizontal projection will yield a single point.

Nonlinearities in the magnetic fields will lead to gradual (on the time scale of a betatron oscillation period) changes in the magnitudes of the transverse amplitude projections. The single point of the turn-by-turn plot will develop, in general, into an area. The distance of a point within this area to the mean position of all the points is a measure of the change of amplitude. The SSC criterion places a limit on the ratio of this change to the mean amplitude. In particular, the rms value of this fractional excursion, termed the "smear," is to be less than 7% within the aperture used for routine beam operations.

The other measure of the departure from linearity is the amplitude dependence of the betatron oscillation tune. The SSC criterion limits the tune range to ± 0.005 within the aperture used for routine beam operations. With some changes in definition, the CERN studies also use smear and tune shift as measures of the departure from linear behavior.

The Tevatron and the SpS present themselves as natural "laboratories" for these experiments. They are proton accelerators with fine linear behavior to which nonlinearities can be added in a controlled fashion. In fact, sextupole magnets already exist in both machines which can be used for this purpose.

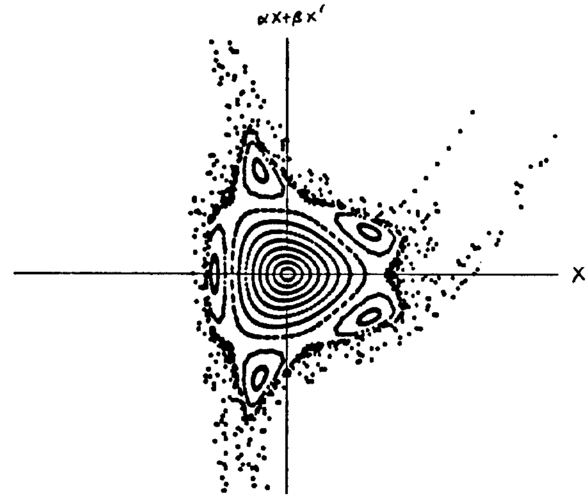

Figure 1: Phase space in the presence of a single sextupole. The small amplitude tune is $\nu = 0.42$. For this case, "islands" of the 2/5 resonance are evident.

An example of the rich phase space structure that can be produced by a single sextupole is depicted in Figure 1. For sufficiently small amplitudes the motion is linear and the phase space trajectories are circles. At larger amplitudes the trajectories assume a triangular cast, reflecting the influence of a distant third-integer resonance. At a particular amplitude an island chain appears. For this particular figure, the small amplitude tune is 0.42 and as the amplitude increases, the tune shifts toward 0.333. The tune at the island chain is 0.400. Eventually, for sufficiently large amplitude, the motion becomes chaotic and unstable.

The experiments described below examine all of these phase space characteristics, with emphasis on comparison between measurement and prediction. In addition, these activities serve as stimuli for instrumentation improvement and the development of techniques to study more complex problems in phase space dynamics.

In addition to the Tevatron and SpS experiments, studies have been performed in the Fermilab Main Ring in an attempt to understand the particle behavior at the injection energy. Here, the environment is inherently nonlinear and thus the situation is the reverse of that which obtains in the other two experiments; from the observations one hopes to deduce the origin of pathologies and devise cures. The Main Ring was not designed with a linear aperture criterion in mind and the challenge is to achieve such performance 20 years after the fact.

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2 Tevatron Experiment E778

Fermilab experiment E778 has developed into a collaborative effort in the study of nonlinear dynamics and beam diagnostics involving accelerator physicists from the SSC Central Design Group, Cornell, SLAC, CERN, and Fermilab. The overall report of the collaboration has been published elsewhere. [1] An account also appears in these proceedings.[2]

2.1 Experimental Conditions and Techniques

The original beam position monitor system in the Tevatron was capable of recording the motion of the center of charge of the beam for one thousand turns. An upgrade for this experiment extended the capability to the million turn level. [3] The positions at two neighboring monitors, coupled with a knowledge of the intervening optics, can be used to find the transverse velocity of the beam at either monitor. Thus, a phase space plot can be obtained for the turn-by-turn motion.

For the E778 experiment, 16 sextupoles were used. Though a variety of configurations is possible, thus far they have been powered so as to produce a strong third-integer resonance driving term. Measurements were performed at tunes far from the 1/3 resonance to study the more complicated phase space structure exhibited there. The two transverse degrees of freedom were sufficiently decoupled so that this in effect is a one degree-of-freedom experiment. All measurements were conducted at the Tevatron injection energy of 150 GeV.

Four basic types of measurements were carried out. The first type of experiment consisted of injecting, ramping the sextupoles up, and firing a kicker magnet. Turn-by-turn signals from two monitors were recorded and analyzed to yield smear and tune values.

In the second, the nonlinearities were on when beam was injected into the Tevatron and a variety of orbit and profile measurements were performed with intentional injection steering errors to look for evidence of degradation in short-term beam behavior.

In the third, the emittance of the beam was slowly increased through the introduction of noise into the transverse dampers and the limiting emittance observed as a function of sextupole excitation.

The fourth variety of measurements was associated with the study of resonance islands, the intent being to observe the trapping and stability of particles in them.

If the beam were a single particle, then at first glance the calculation of the smear would reduce to a simple matter of minimizing an appropriate least squares sum. The finite emittance and momentum spread of the real beam make for difficulties in both the experimental procedures and in the data analysis. In particular, the nonlinear tune variation with amplitude caused by the sextupoles leads to a decoherence of the transverse motion. The extraction of the phase space distortion in the face of this effect relies on a reconstruction of single-particle motion by fitting a Gaussian to the apparent amplitude reduction.

2.2 Results

The smear of the Tevatron in the absence of the additional sextupoles has been measured and is indeed small. Figure 2 displays smear and tuneshift curves derived from perturbation theory as well as data for one of the several working points at which measurements were made.

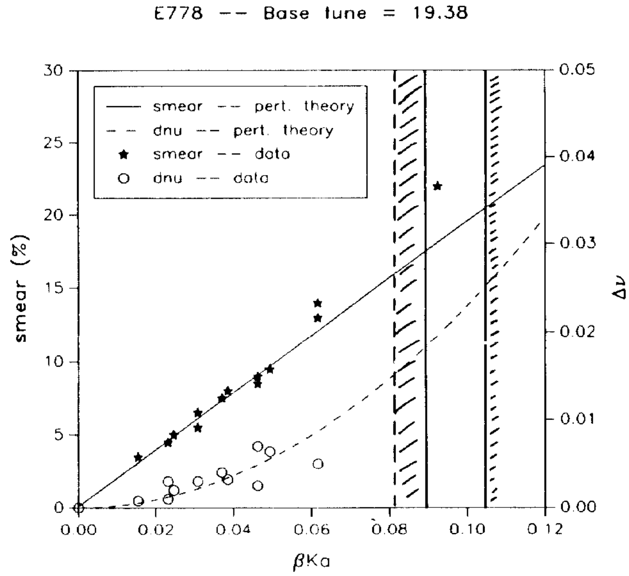

Figure 2: Smear and tuneshift for the E-778 experimental conditions at a small amplitude tune of 19.38. The abscissa is the product of the amplitude function, the sextupole strength, and the oscillation amplitude. The vertical lines indicate the measured (left) and calculated (right) dynamic apertures.

In the injection experiment, no significant variation or deterioration in beam trajectory information was revealed even at the highest sextupole excitation. Long-term losses occur during the injection experiment at high sextupole excitations. They could be dramatically reduced by turning off the RF cavities.

The straightforward dynamic aperture measurement yielded the results presented in Figure 2. At low sextupole excitations, the dynamic aperture is outside of the physical aperture; the data used in the figure is at the higher sextupole currents. The width of the vertical bar representing the measurements spanning a range of a factor of two in sextupole excitation confirms the scaling implied by the combination of variables used for the abscissa.

Trapping of particles in resonance islands was observed at tune values whose fractional parts were 2/5, 3/7, and 5/13. The 2/5 resonance was studied in further detail and is discussed elsewhere. [1], [2], [4]

3 CERN SpS Experiments

3.1 Experimental Conditions and Techniques

The CERN experiments have been conducted at an energy of 120 GeV in the SpS, where the fields are known to be very linear. The sextupoles used are those normally used for third-integer slow spill extraction. Two sextupole configurations have been studied [5],[6]; one in which the third-integer resonance was strongly excited, and one in which it was not. The beam emittance was gradually enlarged until beam losses occurred, thus identifying the dynamic aperture. Flying wires and beam scrapers were then used to measure the aperture and the results were compared with simulation.

A recent set of measurements [7] using a new turn-by-turn diagnostics system allowed for phase space measurements similar to those performed by experiment E778. With this system, the amplitude dependence of the tune was directly measured and compared with simulation. As in the E778 experiment, a slow beam loss could be observed at strong sextupole excitations and one of the studies attempted to measure the rate of this diffusion. To do so, a beam scraper was used to intercept the beam at a particular amplitude. The beam intensity acquired a specific lifetime caused by the diffusion of particles into the scraper. The scraper was then retracted a small amount (2 mm) and the time required for a new exponential lifetime to develop was recorded. By repeating this process for several scraper positions, the diffusion rate as a function of amplitude was obtained.

3.2 Results

Beam profile measurements in the 1986 experiments showed the skewed particle distribution characteristic of the third-integer resonance. Under this sextupole configuration, the dynamic apertures measured at several working points were consistently about a factor of two smaller than those predicted by short-term tracking. Figure 3 shows the smear and tune shift as functions of amplitude obtained by tracking for a particular working point. The measured and dynamic apertures, as well as those determined by short-term tracking, are indicated by vertical lines.

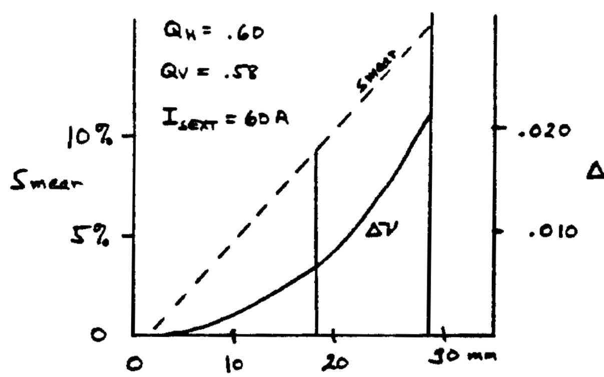

Figure 3: Smear and tune shifts vs. amplitude as derived from short-term tracking. The third-integer resonance is strongly excited. The vertical lines indicate the measured (left) and predicted (right) apertures.

The short-term tracking used in these figures assumed that the beam trajectory passed through the middle of the strong sextupoles. In reality, this was not the case. Horizontal peak-to-peak excursions on the order of ± 20 mm, and vertical excursions of ± 8 mm are typical at 120 GeV in the SpS. By introducing closed orbit errors of this magnitude into the tracking calculations, certain error distributions could be found for which the predicted and the observed dynamic apertures were associated with a coupling resonance. The result of one such simulation is shown in Figure 4. The experimental situation described by these data is one in which the sextupoles were configured so as not to drive the third-integer resonance.

Another experiment was performed in 1988 during which the tuneshift with amplitude was measured. The observed tuneshift agrees well with the prediction. The experiment and its results are described in another paper in these proceedings [8]. For this and subsequent experiments the sextupoles were arranged so that the third-integer resonance was not being driven.

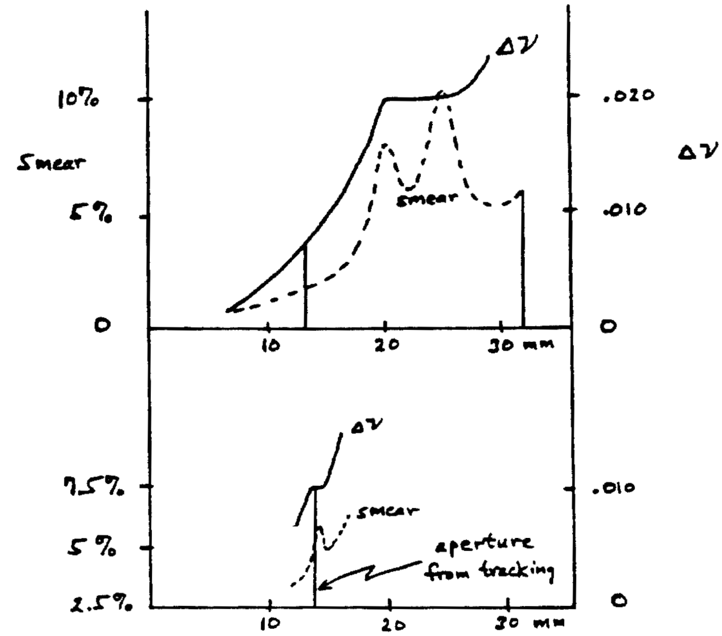

Figure 4: Effect of closed orbit errors on dynamic aperture in the CERN experiments. The top graph shows smear and tune shift as functions of amplitude, determined from short-term tracking in the absence of orbit errors. The bottom graph shows the same for long-term tracking in the presence of orbit errors. The vertical lines are apertures as in Figure 3.

The sextupole induced diffusion experiment was performed with the SpS in storage mode and with the RF turned off. The base tunes were $\nu_x = .63$, $\nu_y = .56$. Using the technique described in the preceeding subsection, it was found that the diffusion rate was 3 mm/minute at an amplitude of 12.6 mm, while it was 6 mm/min. at an amplitude of 15.4 mm. With the scraper at an initial position corresponding to an amplitude of 18.1 mm, no change in beam lifetime is measurable by retracting the scraper further. In other words, the diffusion rate at that amplitude is so large it cannot be measured with this procedure. With the sextupole setting and tune used for this measurement, tracking predicts a smear of 1.5% and a tune shift of $\Delta\nu = .006$ at an amplitude of 13 mm.

At a second working point, ($\nu_x = .595$, $\nu_y = .54$) another measurement revealed a diffusion rate of 0.8 mm/min. at an amplitude of 10.6 mm. At 9.2 mm, the diffusion rate was hardly measurable (less than 0.1 mm/min.). The smear (as determined from tracking) at this amplitude is about 1%, while the tune shift is $\Delta\nu = 0.003$. The causes and mechanisms of the observed diffusion remain to be studied. It should be noted that no diffusion was observed at all when the sextupoles were not energized.

4 Fermilab Main Ring Studies

Systematic dynamic aperture experiments in the Main Ring began in 1987 when the laboratory was considering alternate injection energies for the machine. At the present injection energy of 8.9 GeV, the beam intensity lifetime is poor, on the order of 5 sec. or worse. During the acceleration cycle, by the time an energy of about 20 GeV is reached, no beam loss is observed. To account for this behavior, studies were initiated [9] using newly installed flying wire beam profile monitors and beam scrapers.

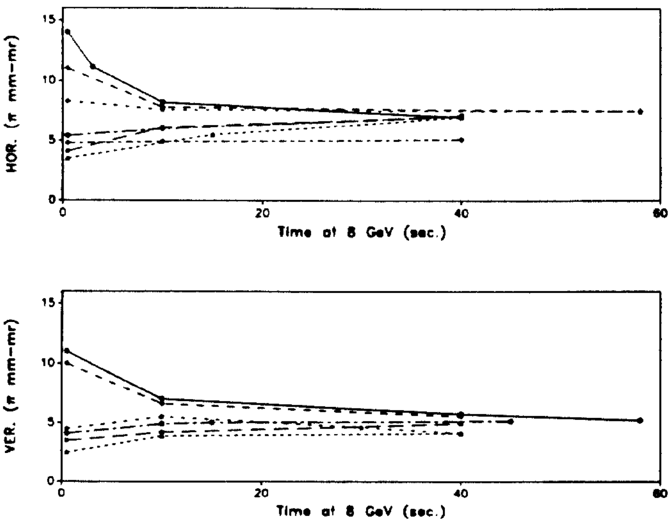

Figure 5: Emittance vs. time for beam with varying injection emittances.

4.1 Observations

Unlike the experimental situations found in the Tevatron and the SpS at 120 GeV, the Main Ring injection environment is such that the natural dynamic aperture is on the order of the emittance of the incoming beam from the Booster synchrotron; in many instances it is smaller. One of the more striking results of the Main Ring experiments is the time development of the beam emittance toward an equilibrium value. This development is indicated in Figure 5. The horizontal and vertical emittances are plotted as functions of time for up to 60 sec. after injection. The large initial emittances (12-14 π mm-mr; 95%, normalized) are indicative of high intensity beams from the Booster. The smaller emittances were obtained using the injection line scrapers. As can be seen, equilibrium emittances ($\epsilon_x \sim 7\pi$ mm-mr, $\epsilon_y \sim 5\pi$ mm-mr) are obtained after about 25-30 sec. at 8.9 GeV.

The development of the beam intensity lifetime as a function of time has also been recorded, as shown in Figure 6. The logarithmic vertical axis allows one to see just when the final equilibrium

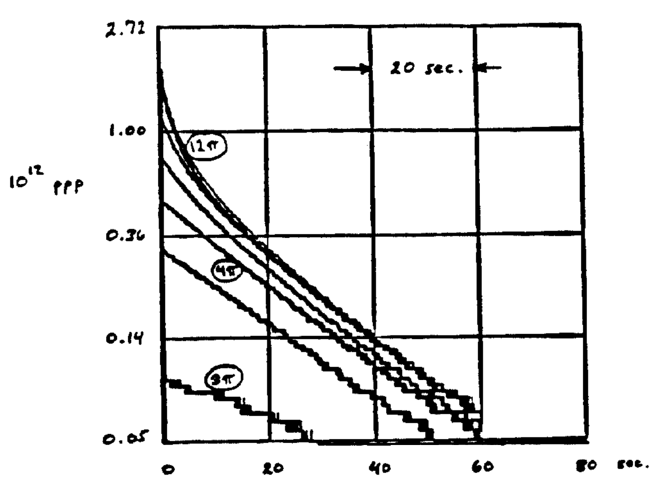

Figure 6: Main Ring beam intensity vs. time at 8.9 GeV for various incoming emittances.

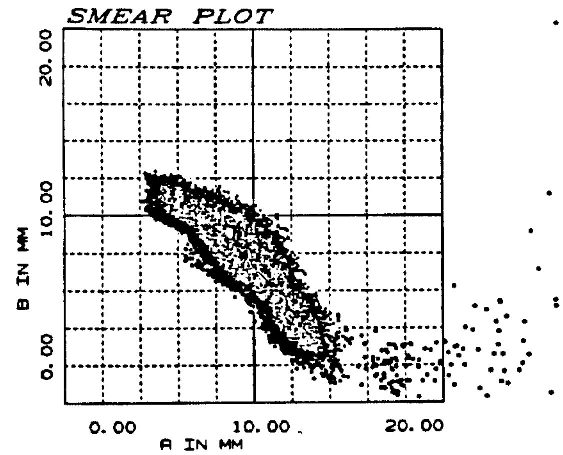

Figure 7: Particle tracking result at 8.9 GeV in the Main Ring.

lifetime is reached. As can be seen, the large incoming beams have a short lifetime which lengthens as time goes on, while the smaller incoming beams start out with a longer lifetime, as expected.

The initial Main Ring measurements of 1987, at both 8.9 GeV and 20 GeV, indicated that the emittance growth rates and, upon reaching an aperture, the equilibrium lifetimes were consistent with beam-gas scattering, at least to first approximation. [10] Later experiments, involving variation of vacuum pressure within the beam chamber, have supported this model. With this understanding, subsequent studies have concentrated on the source of the aperture.

In early experiments it was noted that turning off the RF system dramatically increased the intensity lifetime. Recent experiments have shown that the emittance growth due to RF noise is negligible and that it is indeed the dynamic aperture which increases when synchrotron oscillations are not present. This also confirms that the aperture restriction at injection is dynamic in nature as opposed to physical.

The equilibrium emittances and lifetimes observed in the study described earlier are manifestations of a particular operating point. Measurements of equilibrium lifetime and dynamic aperture at various other operating points have been performed and the fifth-integer resonance lines are clearly shown to be sources of a reduction in the dynamic aperture.

4.2 Comparison with Simulation

In contrast with experiment E778 and the CERN SpS experiments, the sources of the Main Ring's nonlinearity are not well known and certainly are not under the experimenter's control. Hence, one cannot as easily predict the behavior of particles under particular experimental conditions, but must attempt to develop a model of the machine which explains the behavior observed.

Magnetic measurements have been performed on a subset of Main Ring dipoles. The multipole distribution has been used in tracking studies as reported elsewhere [11], [12], [13]. An interesting feature of the tracking calculations is illustrated by Figure 7, in which a beam particle apparently stable for many thousands of turns is abruptly lost. The axes represent the "invariant" amplitude of the motion in the horizontal and vertical planes. Uncoupled, linear motion would result in a point on this graph over many turns. For the case shown here, the particle survived 33,000 turns before exhibiting rapid horizontal emittance growth.

5 Aperture and Field Quality

With some slight risk of oversimplifying the situation, present-day synchrotron designs can be divided into two categories: those with intentional nonlinearities and those with unintentional nonlinearities. In the first class are electron rings seeking to achieve very low emittance, such as light sources and damping rings. The focussing is so strong that chromatic effects require strong sextupoles for compensation. In the second class are large superconducting hadron colliders. These synchrotrons can be made close-to-linear by increasing the main magnet coil diameter, by increasing the injection energy, by strengthening the focussing, and so on. These steps would increase the cost of these very expensive facilities, and so some practical means of cost optimization has to be found. Therefore the need arises for an aperture/field quality criterion which allows one to perform parametric studies without having to rely on the ability to do long time-scale simulation of the dynamic aperture.

The development of an aperture criterion requires its own set of criteria. It must be intelligible to everybody — magnet designers, lattice designers, even laboratory directors. It should be brief. It should be physically reasonable, since verification will no doubt take a long time. And, it would also help if the criterion were correct. As in the case of dynamic aperture criteria, the "linear" aperture criterion must also apply to the entire synchrotron, complete with correction and adjustment magnets.

The above list led to the development of an aperture criterion stated in terms of the smear and tuneshift discussed earlier. People tend to agree on what such a criterion should look like — a smear of '__' at an amplitude of '__' mm, etc. The debate begins when numbers are assigned to the blanks. The experiments described in this report are attempts to verify that quantities such as smear and tuneshift are indeed reasonable quantities to use and to provide some insight into what values need be assigned to these quantities in a criterion.

Results of the experiments presented here show good agreement with tracking and perturbation theory for "short term" quantities such as tune shift with amplitude, smear, decoherence, etc., for the one degree-of-freedom cases studied thus far. Future studies will need to include other distributions of nonlinearities in order to more closely model a real accelerator such as the SSC or LHC. The sextupole configurations used to date have simulated either a high smear, low tuneshift regime (where the third-integer resonance is strongly driven) or a low smear, high tuneshift regime (thus far only studied at CERN). Other regions of the smear, tuneshift plane need to be explored, and extension of these studies to two degrees of freedom is necessary.

6 Summary and Concluding Remarks

Purely as investigations in nonlinear dynamics, a gratifying amount of detail of phase space structure has been observed experimentally. With suitable preparation, a beam can exhibit a reasonable approximation to single particle behavior. Entities such as resonance islands that have been previously restricted to theory are now easily measured, opening up a rich subject for further investigation.

In order to achieve adequate agreement with the measurements, the physical content of simulations has been improved. Such effects as synchrotron oscillations, closed orbit distortions, individual magnet field errors, and, at low energy, space charge must be included in the codes. The next step should be long-term tracking of beams to account for the diffusion processes that are observed in the experiments. This implies a major improvement in the algorithms for long-term tracking.

It is too early to judge whether or not the smear-tune shift style criterion is the proper choice. Studies with other sextupole configurations will probably have to be performed in order to separate the effects of the two parameters. It is entirely possible that a quite different criterion will emerge as a result of ongoing study. Meanwhile, these studies may lead to significant improvement of existing machines as well, in particular the aging Main Ring.

Finally, it is interesting to note the changing character of accelerator studies. Substantial preparation is required and extensive analysis of the data is called for; there is a growing resemblance to high energy physics experiments. In fact, E778 went through the same formal approval procedure as a high energy physics experiment and has the training of graduate students as a major goal.

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