AN EXPERIMENTAL STUDY OF THE SSC MAGNET APERTURE CRITERION

N.Merminga, D. Edwards, D. Finley, R. Gerig, N. Gelfand, M. Harrison, R. Johnson, M. Syphers
*Fermi National Accelerator Laboratory,*Batavia, IL 60510*
R. Meller, R. Siemann, R. Talman
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853 U.S.A.
P. Morton
Stanford Linear Accelerator Center, Stanford, CA 94305 U.S.A.
A. Chao, D. Johnson, S. Peggs, J. Peterson, C. Saltmarsh, L. Schachinger
SSC Central Design Group, Berkeley, CA 94720 U.S.A.

Abstract

A beam dynamics experiment, performed in the Fermilab Tevatron, that was mainly motivated by planning for the Superconducting Super Collider (SSC) is described. Nonlinearities are introduced in the Tevatron by special sextupoles in order to simulate the SSC environment. "Smear" is one of the parameters used to characterize the deviation from linear behavior. Smear is extracted from experimental data and compared with calculation over a wide range of conditions. The agreement is excellent. The closed orbit at injection as well as the injection trajectory reveal no deterioration even at the highest sextupole excitations. Measurements of the dynamic aperture are in general agreement with prediction. Particles captured on nonlinear resonance islands are directly observed and measurements are performed for the first time. The stability of the islands under tune modulation is investigated.

Introduction

The specification of the magnetic field quality used in the Conceptual Design Report of the SSC is based on the imposition of bounds to the departure from linear behavior in the oscillation of single particles about their closed orbits. Even though the specification is physically reasonable, it is important to give serious attention to the values assigned to the parameters in the criterion. Fermilab experiment E778 is part of that effort.

If the betatron oscillations of a particle in a synchrotron are linear, then the oscillation amplitude is a constant of the motion and the trajectories of the particles are circles in phase space. Nonlinearities in the magnetic fields will lead to gradual (on the time scale of a betatron oscillation period) changes in the trajectories of the particles. Now the motion is circular only for small amplitudes. For bigger amplitudes the motion is not circular but still stable. The rms deviation from a circle is called "smear". The criterion expressed in terms of the smear, reads: The smear is to be less than 6.4% within the aperture used for routine beam operations.

The first purpose of E778 was to determine if smear is predictable from tracking calculations. A second purpose was to correlate accelerator performance like injection efficiency and particle lifetime with the value of the smear. A third purpose was to investigate the sensitivity of beam dynamics to externally imposed tune modulation.

The Tevatron was considered a suitable laboratory for this experiment because it is a proton accelerator with excellent linear behavior (which was demonstrated as part of the experiment). Moreover a substantial number of sextupole magnets was already installed that could be used as a source of nonlinearity.

Sixteen normal sextupoles are powered in two sets of eight so as to produce a strong third-integer resonance driving term. Measurements were performed at tunes far from 1/3 in order to study the rich phase space structure exhibited in Fig. 1.

*Operated by the Universities Research Association under contract with the U. S. Department of Energy.

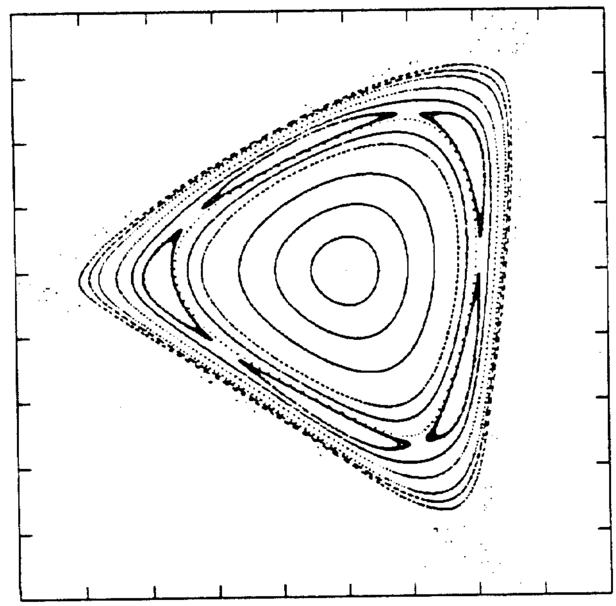

Figure 1: Normalized phase space plot obtained by numerical tracking of particles through an accurate representation of the Tevatron, with conditions set to emphasize nonlinear resonance islands.

The Experiments

The studies were organized in three experiments. All three were carried out at the Tevatron injection energy of 150 GeV. Necessary preliminaries included establishment of small normalized emittance (95%) at or below 15 π mm-mrad, orbit adjustments at the nonlinearities to minimize tuneshifts, reduction of horizontal-vertical coupling, reduction of chromaticity to 3 units or less and minimization of coherent synchrotron oscillations at injection.

Experiment 1. Smear

The objective here is to measure the smear for a variety of conditions and compare with prediction. After injection, the sextupoles were ramped up to the desired setting in 10 seconds, then, after a further 10 second delay, a coherent betatron oscillation was induced by firing the Tevatron injection kicker. The center of mass of the beam was recorded for 1024 to 64,000 turns (in some cases we recorded data up to 500,000 turns[1]) in each of two adjacent beam position monitors (BPM's). Fig. 2(a) shows a typical record of measured values of the transverse displacement at one of the two position monitors for the first 4,000 turns after the beam has been kicked and Fig. 2(b) shows the corresponding values of the amplitude for the first 500 turns.

The damping of the centroid motion observed in Fig. 2(b) can be understood. Nonlinearities introduce dependence of tune on amplitude, $\nu = \nu(a)$. The different particles have slightly different tunes

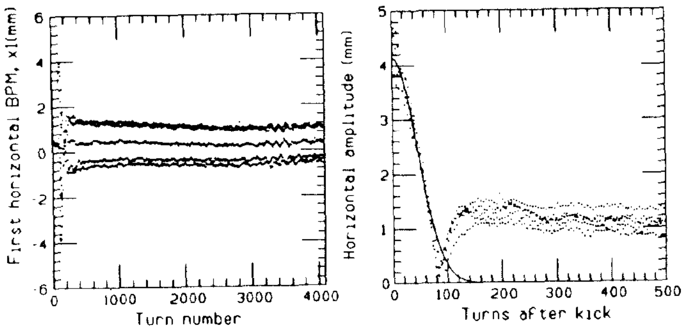

Figure 2: (a). Experimental turn-by-turn position data. (b). Reduction of amplitude of the coherent betatron oscillation with turn number for an initial 4mm kick with sextupoles excited to 25 amperes. The solid line is a fit of the experimental data to a Gaussian.

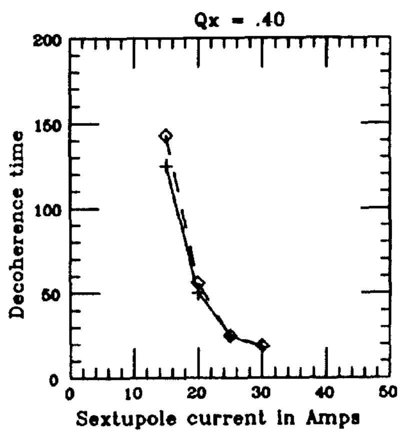

Figure 3: Decoherence time vs sextupole excitation, for base tune 19.40 and initial amplitude 4.5mm. The solid line connects the experimental data and the dashed line indicates the predicted values.

and, though the amplitudes start out in phase, they gradually decohere. Since the BPM measures the centroid of the beam there is an apparent damping. Calculations of the decoherence time agree well with measured values, as Fig. 3 shows. In principal, non-zero chromaticity also has a damping effect on the beam. But, as mentioned earlier, chromaticity compensation had been applied in E778, so as to make this source of tune spread much less important than the effect we described above.

Measurements were made at sextupole excitations of 0 to 50 amperes in steps of 5, for horizontal tunes in steps of 0.01 from 19.38 to 19.42 with oscillations generated by kicker voltages of 5, 8 and 10 kV. In the bare Tevatron, the corresponding oscillation amplitudes are roughly 2.25, 3.6 and 4.5 mm. The smear was extracted in a small number of turns, before the beam decohered. Quantitative comparison between observed and calculated smear is contained in Fig. 4 which shows excellent agreement.

Experiment 2. Injection Experiment/Dynamic Aperture

In this experiment we want to correlate the smear with a performance degradation in the behavior of the injected beam and in the dynamic aperture. The injection experiment consisted of injecting onto the closed orbit and off of the closed orbit by 1.5 mm with the sextupoles on at excitations of 0, 15, 30, 40, 45 and 50 amperes and recording first turn position monitor data, closed orbit at injection, turn-by-turn data at injection and beam intensity versus time. Even at the highest excitations, the first three items revealed no deterioration in information content. The conclusion is that it would be possible to

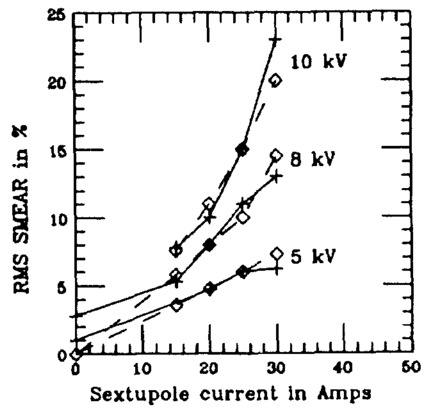

Figure 4: Plot of smear vs sextupole current for base tune 19.39 and 3 different values of the kicker voltage, 5, 8 and 10 kV, corresponding to 2.25, 3.6 and 4.5 mm in amplitude. The solid curves connect the experimental data while the dashed lines connect the predicted ones.

diagnose and correct injection problems in the presence of these strong nonlinearities.

The beam intensity though, as a function of time showed a slow loss over approximately 10 seconds. The fact that the time structure of the loss contained a component at the synchrotron frequency was a hint that the longitudinal motion plays a role. Indeed most of the loss disappeared when we repeated the experiment with the RF turned off.

The dynamic aperture measurement was done by increasing the beam emittance by injecting noise into the dampers and observing the resulting beam size limit with the flying wires. Comparison with calculations shows reasonable agreement[2].

Experiment 3. Resonance Islands and Tune Modulation

The goal now is to observe directly capture of particles into stable nonlinear resonance islands, measure quantities of interest such as the capture efficiency and study the influence of external tune modulation on the stability of these islands.

By deflecting the beam with the sextupoles turned on to give resonance islands and the magnitude of the transverse kick properly adjusted, some of the particles are captured on the stable islands. This manifests itself by the absence of decoherence. Particles on one of these islands exhibit a tune of *exactly* 2/5, which defeats the decoherence. This accounts for the signal persisting after a few hundred turns in Fig. 2(a) and 2(b). Signals like this have been observed to persist for some minutes (about a million turns). That there are five distinct traces in Fig. 2(a) reflects the resonance nature and spectral analysis yields a value $\nu = .400010 \pm .000005$ as expected. Fig. 5 shows a "raw" data plot of the signal from the first BPM versus the signal from the second BPM for some thousands of turns taken after some seconds and the 5 islands are clearly visible. The "logo" in the corner of the plot is a demagnified view of the same data with successive points joined by straight lines. The point lands only on every second island, confirming the 2/5 identification.

To quantify the production probability the "capture efficiency" was defined as the fraction of non-decohering charge surviving 500 turns, well after the decoherence of uncaptured particles and before appreciable decay has occurred. Experimentally, with kicker voltage held fixed, the capture efficiency was measured as the base tune was varied. The result is plotted in Fig. 6 where a classical resonance response is observed.

The decay mechanism for loss of particles out of the stable islands is not yet fully understood. To investigate this and to extract the rotation period near the center of the island, ν_R, the data of Fig. 7 were obtained. The island decay rate was measured as the base tune was sinusoidally modulated with a tune range of $\delta\nu$, at a frequency ν_M.

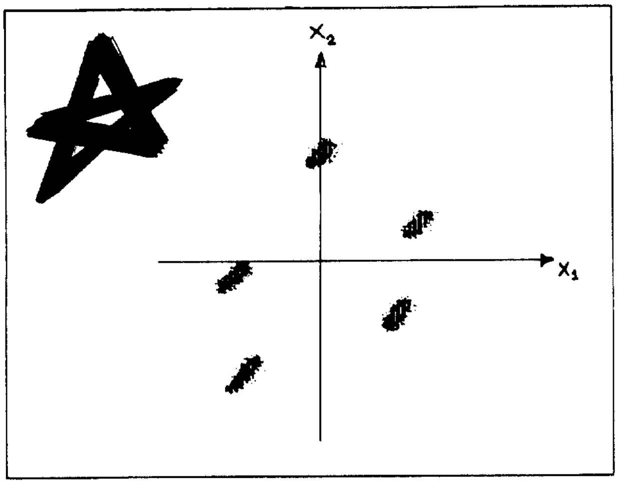

Figure 5: "Raw" data plot of the first BPM vs the second BPM for 10,000 turns taken about 1 second after the kicker fired. The "logo" is a different view of the same data with successive points joined by straight lines.

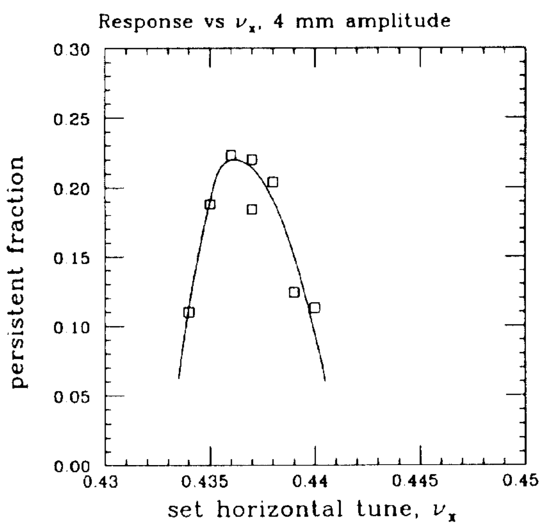

Figure 6: Plot of the capture efficiency as a function of the base tune for an initial amplitude of 4 mm.

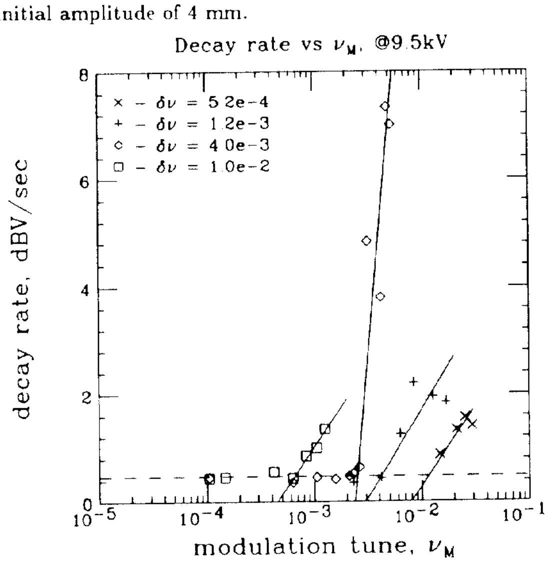

Figure 7: Plot of the island decay rate as a function of the modulation tune illustrating transition from adiabatic to nonadiabatic behavior. Various symbols correspond to various modulation amplitudes.

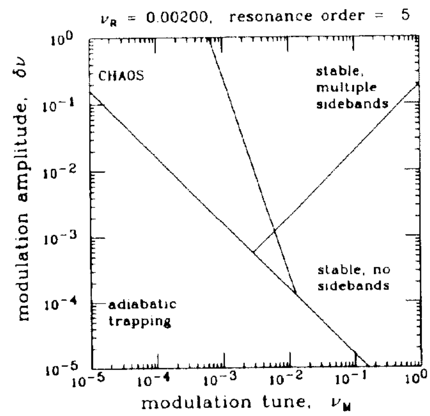

Figure 8: Plot outlining schematically the regions of stability associated with tune modulation.

As ν_M was increased at fixed $\delta\nu$ the decay rate remained small until a rather sharp break point was reached, beyond which the decay rate increased rapidly; see Fig. 7. We call this a transition from adiabatic to nonadiabatic behavior where our picture of adiabatic behavior[3] has the resonance islands "breathing" in and out, radially in phase space, at a rate sufficiently slow that the particles remain trapped. The location of the break point and the adiabatic condition can be used to estimate ν_R. Peggs has suggested that the ideas of Chirikov and others be incorporated in a ν_M, $\delta\nu$ "phase-diagram" of Fig. 8 where the non-adiabatic region is itself divided into distinct phases: one chaotic and one non-chaotic, with the latter further subdivided into regions with and without sidebands.[4] Relevant observations though have not yet been made.

Acknowledgments

The contribution of our CERN colleagues, Alain Hilaire and Luc Vos, is greatly appreciated.

References

[1] S. Peggs, C. Saltmarsh, R. Talman, Million Revolution Accelerator Beam Instrument for Logging and Evaluation, March 1988, SSC-169.

[2] J. M. Peterson et al., Dynamic Aperture Measurements at the Tevatron, this conference.

[3] A. W. Chao, M. Month, Nucl. Instr. and Meth, 121, 129 (1974).

[4] A. W. Chao et al., An Experimental Study of the SSC Magnet Aperture Criterion, January 1988, FN-471, SSC-156.