DYNAMIC APERTURE MEASUREMENTS AT THE TEVATRON

J. M. Peterson, A. W. Chao, D. E. Johnson, S. G. Peggs, C. G. Saltmarsh and L. C. Schachinger
SSC Central Design Group

D. A. Edwards, D. Finley, N. M. Gelfand, R. E. Gerig, M. Harrison,
R. P. Johnson, N. Merminga, and M. Syphers
Fermi National Accelerator Laboratory

R. M. Talman, Newman Laboratory of Nuclear Studies, Cornell University

P. L. Morton, Stanford Linear Accelerator Laboratory

Abstract:

The dynamic aperture of the Tevatron perturbed by an array of 16 sextupoles was measured by a set of flying wire scans taken as the horizontal emittance was blown up by means of the noise-modulated "damper" system. Both the betatron width and the momentum-dispersion width were measured. Computer simulations with a simplified lattice agree with the measured dynamic apertures at high sextupole excitation. They illustrate that the dynamic aperture was due to the nearby sextupole-driven third-integer resonance. Near zero excitation the beam size was limited apparently by the physical aperture. The measured "smear" aperture (6.4% rms) was about half the measured dynamic aperture over the range of observation.

1. Introduction

The dynamic aperture due to a controlled array of 16 sextupoles[1] inserted into the Tevatron "fixed-target" lattice was measured and compared with computer simulations.

2. Experimental Procedure

The basic procedure was to blow up the horizontal emittance of the 150 GeV injected beam in the Tevatron by means of a noise-modulated "damper"-magnet system driven at a level at which beam loss became apparent on a one-minute time scale. The betatron tunes of the fixed-target lattice were set at $Q_x = 19.3715$ and $Q_y = 19.46$.

In order to avoid a longitudinal multi-bunch instability, which had confused the results in a preliminary experiment, the RF voltage was turned off and the RF cavities detuned. The 20-bunch beam train was observed to debunch and smear around the ring, as expected from the measured energy spread ($\sigma_E/E \simeq 1.4 \times 10^{-4}$). By 32 seconds after injection the beam distribution around the ring was seen to be fairly uniform from flying wire scans taken at 120° intervals in the beam revolution period. Analysis of the flying-wire data indicated no growth in the energy spread of the beam after injection.

The noise-modulated horizontal "damper" magnet was turned on at 32 seconds after injection. With no excitation of the sextupole array, beam loss became apparent about 1 minute after turn-on of the noise-modulated excitation. With 30 amperes in the sextupole circuit, beam loss began immediately, and the characteristic loss period was about 1 minute. Flying-wire data were taken at several times up to 102 seconds after injection, so as to judge when the beam reached its final dimensions corresponding to the limiting aperture.

3. Analysis of the Data

Three flying wires were used -- two flying in the horizontal direction and one in the vertical. The two horizontal wires was situated at points of quite different dispersion in order to extract the energy width of the beam as well as the betatron amplitude. A typical set of flying-wire data taken at 32, 62, 82, and 102 seconds after injection is shown in Figure 1(a). Note that the beam distribution, which initially is symmetric, develops a pronounced left-right asymmetry as it is blown up. Such an asymmetry is to be expected on the basis of the phase-plane plot from corresponding computer simulation shown in Figure 1(b). This plot, which had the same triangular shape at all sextupole excitations, illustrates that the dynamic aperture is due to the nearby third-integer resonance. No change was observed in the shape or width of the vertical profile, indicating that horizontal-vertical coupling was not significant in this experiment.

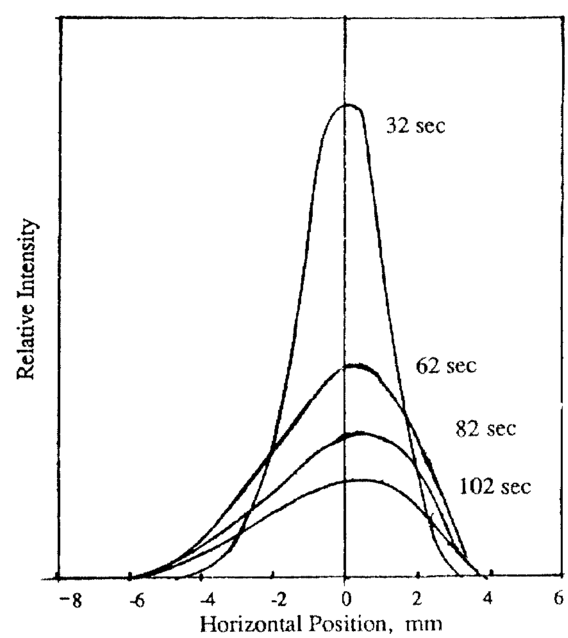

Figure 1(a). Horizontal beam distributions at flying wire HC48 taken at 32, 62, 82, and 102 seconds after injection.

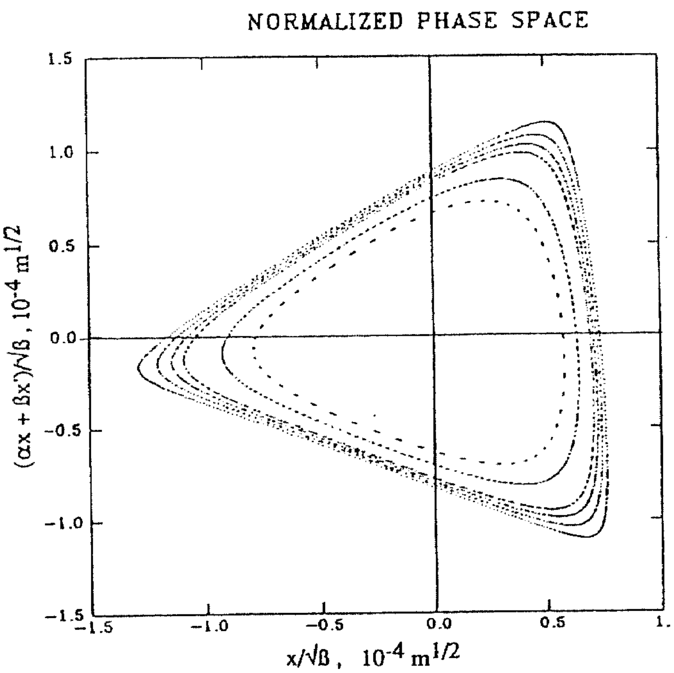

Figure 1(b). Typical phase space distributions close to the dynamic aperture, referred to the HC48 location.

For the measurement of the dynamic aperture, only the base width of an aperture-limited beam distribution has significance. Because of the asymmetry it is convenient to use the full width rather than a "half-width". We take the total full width to be the algebraic sum of the betatron and energy-dispersion full widths. The momentum-dispersion width of the beam was relatively small. At flying wire HC-48 (β_x = 104m, η_x = 1.9m) the full momentum width was 0.8mm.

For the computer simulations a simplified lattice was used which was perfectly linear except for the 16 sextupoles. It was found over a considerable range of parameters that the computed dynamic aperture A_D (full width at flying wire HC-48) was well represented by the relationship

$$A_D(\text{mm}) = 5.5\times10^3(Q_x-1/3)/I_s$$

where Q_x is the fractional horizontal betatron tune at small amplitude, and I_s is the current in the string of sextupoles (in amperes). Such a relationship is expected near a sextupole-driven, third-integer resonance from analytic theory.

4. Results

The measured and computed dynamic apertures at the position of flying wire HC-48 are shown in Figure 2. The agreement at high sextupole excitation is satisfactory, considering the systematic uncertainties involved in the computer simulations. These uncertainties were, one, an uncertainty in the closed orbit at the sextupoles, which affected the betatron tune and thus, through the dynamic-aperture relationship mentioned above, affected the computed apertures. A shift in the average closed-orbit at the 16 sextupoles of 0.25 mm will change the computed dynamic aperture by about 3.5 mm at each sextupole setting. A second uncertainty is the effect of the strong sextupole due to the persistent currents in the superconducting Tevatron dipoles, which has not yet been included in the computations. (The sextupoles correcting the natural chromaticity were checked and found to have a negligible effect on the aperture.) A third consideration is that the computations were limited to a few hundred turns so that the computed aperture is an upper bound, whereas the experiment involved several million revolutions.

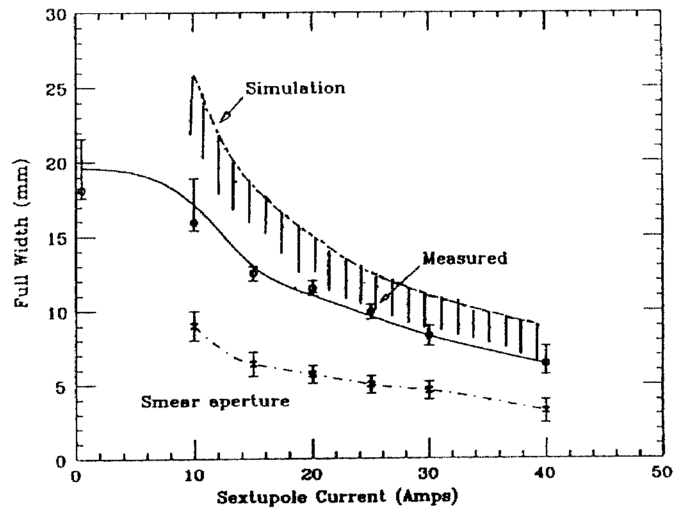

Figure 2. The measured and computed dynamic aperture due to the 16-sextupole array at various excitations. The computed aperture is considered an upper limit. The shaded area indicates the range of uncertainty. Also shown is the aperture at which the sextupole array produces a rms smear of 6.4%.

At low sextupole excitation the measured aperture levels off at about 20 mm, full width, due presumably to a physical aperture, such as a septum magnet. The vacuum chamber has an inner diameter of about 60 mm. The data at zero and 10 amperes of sextupole excitation are consistent with the aperture being due to a fixed physical obstruction.

The smear aperture curve in Figure 2, which is the diameter of a beam with an rms smear of 6.4%, was obtained from the data of a separate experiment.[1] The accelerator parameters for the smear-aperture curve match those used for the computed dynamic-aperture curve. The smear aperture is about 0.5 of the measured dynamic aperture and about 0.4 of the computed aperture. The analytic estimate[2] of this ratio at this lattice point is 0.41, which supports the conjecture that the megaturn dynamic aperture in a real machine can be appreciably less than that computed in a few-hundred-turn simulation.

Conclusions

We have measured the dynamic aperture produced by an array of 16 sextupoles inserted into the Tevatron lattice. The results are in reasonable agreement with computer simulations. It was observed that the dynamic aperture is about twice the aperture at which the sextupole-induced rms smear is 6.4%.

Acknowledgment

It is a pleasure to acknowledge the very able participation of A. Hillaire of the SPS Division of CERN in this experiment.

Reference

[1] N. Merminga et al., Paper "An Experimental Study of the SSC Magnet Aperture Criterion," this conference.
[2] Etienne Forest, private communication.