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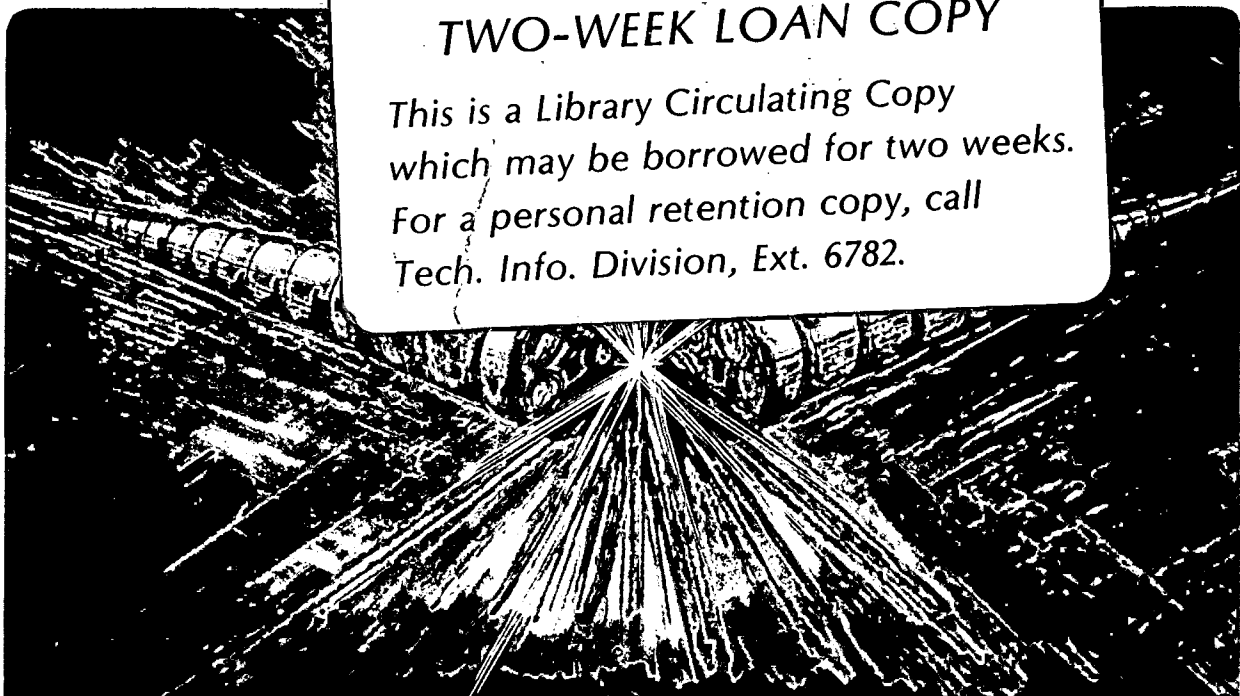
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A. Garren, M. Cornacchia, and F. Dell

August 1983

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CHROMATIC PROPERTIES AND TRACKING STUDIES OF A 20 TeV pp COLLIDER

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The chromatic properties of a lattice for the 20 TeV pp collider described in an accompanying paper have been investigated. Since this machine has a low β -function value at the interaction points ($\beta_{x,y} = 2$ m), the large value in the nearby quadrupoles is a major source of perturbations for off-momentum particles. Preliminary tracking studies have been performed in an attempt to determine the dynamic aperture. The model includes the effects of chromaticity sextupoles, octupoles to straighten the working line, random multipoles simulating magnet construction errors and closed orbit distortions.

Magnetic Imperfections and Their
Effects on the Beam Dynamics

A typical high field (8T) SSC magnet is expected to have a smaller aperture and coil radius than any superconducting magnets built so far for accelerators. The smaller coil radius increases the sensitivity of the field to the constructional errors of the magnets. For the purpose of estimating these errors and their effect, we have taken a model of a high field superconducting magnet where the field behavior is determined by the coil location rather than by the iron shape.

We express the magnetic imperfections in terms of the coefficients of the multipolar expansion of the field, defined as

$$\frac{\Delta B}{B_0} = \sum_n b_n x^n \quad (1)$$

Where $\Delta B/B_0$ is the field error relative to the main bending field B_0 in the horizontal mid-plane due to the n -th multipolar coefficient at a distance x from the magnet center. The b_n coefficients denote the "normal" field; the "skew" coefficients are indicated by the symbol a_n .

The magnetic imperfections are usually classified as systematic and random. The latter is the scatter of the multipole coefficients around the systematic or mean values. The purpose of this study is to investigate the short term effects of random magnetic imperfections.

It is thought that the main cause of scatter of the magnetic multipoles, represented by the r.m.s. value $\langle \Delta b_n \rangle$, is inaccuracy in coil position, and is given by the approximate formula (Ref. 1).

$$\langle \Delta b_n \rangle = C (n + 1) \langle \delta \rangle R_c^{-(n+1-k)} \quad (2)$$

Where $\langle \delta \rangle$ is the r.m.s. positioning error of the coils, R_c the average distance of the coils from the magnet axis (coil radius), and C is a constant

which depends on the construction details of the coils and of the iron. The value of k is zero or one for dipole or quadrupole magnets respectively. Equation (1) shows that the smaller the coil radius, the slower the decrease of multipole strength as a function of the order of the multipole.

We have estimated the values $\langle \Delta b_n \rangle$ to be expected in small aperture magnets by scaling them from the measurements and the tolerances of the CBA magnets (Ref. 2). The average coil radius in the CBA magnets is 7.4 cm and the vacuum chamber radius 4.4 cm. For the SSC magnets we have assumed an average coil radius of 2 cm and a vacuum chamber radius of 1.5 cm. We have also assumed that the coil positioning error is the same in CBA and SSC ($\langle \delta \rangle = 0.05$ mm). Since a smaller aperture magnet has fewer current blocks we have reduced the strength of the multipoles, as given by Fig. (2), by a factor R_c . In summary, the following scaling law has been applied:

$$\frac{\langle \Delta b_n \rangle_{SSC}}{\langle \Delta b_n \rangle_{CBA}} = \left(\frac{R_{C,CBA}}{R_{C,SSC}} \right)^{n-k}$$

where $k = 0$ for dipole and $k = 1$ for quadrupole magnets.

Table I lists the r.m.s. values calculated according to this scaling law. The multipoles b_1 to b_4 and a_1 to a_4 in the dipoles have been scaled from the measurements of 10 CBA dipoles. We have assumed that the width of the distribution of the measured data corresponds to ± 3 standard deviations. The $b_5 \dots b_{12}$, $a_5 \dots a_{12}$ multipoles in the dipoles and $b_1 \dots b_{12}$, $a_1 \dots a_{12}$ multipoles in the quadrupoles have been scaled from the CBA tolerance guidelines. Since these were based on the position accuracy of the coils of 0.05 mm r.m.s., the resultant estimates for the SSC magnets are consistent with our model.

In our preliminary study we have not considered the effect of the dipole terms a_0 , b_0 , which affect the closed orbit. We have not yet included the effect of systematic imperfections: they affect the tune variation across the momentum aperture, drive structure resonances and couple with the closed orbit errors to give an effective scatter of lower order multipoles. The strengths of the systematic imperfections depend on the construction details of the coils and, at least for the lower multipoles, can be corrected.

Model Machine

The SSC collider modeled is the pp lattice presented at this conference³, a double ring machine with six crossings and three superperiods. We have put delta-function multipole kicks at the center of every quadrupole, and between pairs of dipoles. The calculations of this paper were made with the program PATRICIA^{4,5}.

The betatron tunes may not yet be optimized. The lattice as first worked out for the Cornell

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Table I

Random Multipole Errors Assumed for SSC Magnets

n	dipoles		quadrupoles	
	b_n, a_n (cm ⁻ⁿ)		b_n, a_n (cm ⁻ⁿ)	
1	1.6×10^{-4}		4.1×10^{-5}	
2	7.8×10^{-5}		4.1×10^{-5}	
3	2.2×10^{-5}		1.6×10^{-5}	
4	3.6×10^{-5}		1.0×10^{-5}	
5	2.2×10^{-5}		6.0×10^{-6}	
6	1.3×10^{-5}		3.5×10^{-6}	
7	7.3×10^{-6}		2.0×10^{-6}	
8	4.2×10^{-6}		1.1×10^{-6}	
9	2.3×10^{-6}		6.1×10^{-7}	
10	1.3×10^{-6}		3.4×10^{-7}	
11	7.1×10^{-7}		1.8×10^{-7}	
12	3.8×10^{-7}		9.7×10^{-8}	

workshop had $\nu_x = \nu_y = 85.31$. We planned to shift to 85.39, 85.37 - closer to the 1/2 and farther from the 1/3 integer stopbands, to a point analogous to one that worked well for a 2-in-1 CBA lattice studied earlier⁶. We found that the half-integer stopband considerably increased the momentum beta function dependence so we moved further below the 1/3 integer, to 85.297, 85.307. It may be that even lower tunes will be better.

Only two families of chromaticity sextupoles were used. Each cell (including the dispersion suppressor cells) contained one SF and one SD sextupole, with centers 1 m from the neighboring QF or QD quadrupole. The sextupole locations were symmetrized with respect to the arc centers, so the center quadrupole had two adjacent sextupoles.

Closed Orbit Errors

In addition to the random multipole errors, we have also simulated the effects of closed orbit error in an approximate way by applying kicks due to the multipole fields that would apply to a particle with a closed orbit offset. These offsets are taken to be random and uncorrelated from magnet to magnet, scaled with $\sqrt{\beta}$, and normalized to 1 mm rms displacement.

Combinations of Errors Studied

We have studied chromatic effects and tracked orbits for five situations that differ in their combinations of three types of errors. In all cases we have adjusted the strength of the cell quadrupoles to restore the original $\Delta p = 0$ tunes (85.297, 85.307), the chromaticity sextupoles to give zero chromaticity at $\Delta p = 0$, and a systematic octupole component in the cell quadrupoles to make the tunes at $\Delta p/p = \pm 0.025$ about equal to the central tunes.

The three types of errors considered are:

1. Random multipoles of order 3-12. The suppression of orders 1 and 2 is intended to represent the machine when the nearest second and third order resonances have been corrected.
2. Random multipoles of order 1 and 2 (quadrupole, sextupole).
3. Closed orbit error.

We have adopted a shorthand labeling scheme (k_1, k_2, k_3) where $k_i = 1$ or 0 when an error of type i

is or is not included. Thus (0,0,0) is the perfect machine, (1,0,0) includes multipoles of order 3-12, etc.

Chromatic Behaviour

The dependence of the tunes and orbit functions on momentum deviation is shown in Figs. 1-5 for the cases (0,0,0) - the perfect machine, and (1,1,1) - all errors included. In the latter case the systematic quadrupole, sextupole, and octupole strengths have been adjusted to restore the original tune dependences as well as possible. The dotted vertical lines at $\pm 0.05\%$ represent a generous estimate of the maximum momentum width of the beam. The reason to include the much larger momentum range, to $\pm 0.45\%$, is to show the effort of moving the beam across most of the physical aperture, which is ± 15 mm.

We see that the tunes and dispersion remain quite flat out to $\Delta p/p = \pm 0.25\%$, while β_{max} approximately doubles. Since the dispersion $X_p = 2.9m$ this interval represents half of the physical aperture and five times the maximum beam momentum width. Thus the chromatic properties of the ring appear quite satisfactory.

Tracking and Dynamic Aperture

Particles were tracked in model machines with five error combinations over the momentum range $-0.45\% < \Delta p/p < +0.45\%$ at intervals of 0.05%. Runs with 50, 100, 200, 400, and 800 turns were made for various initial amplitudes. We searched for stability limits, assumed to be between the amplitude of a particle that survived and one that was lost, i.e., passed the physical aperture of 15 mm, during the run.

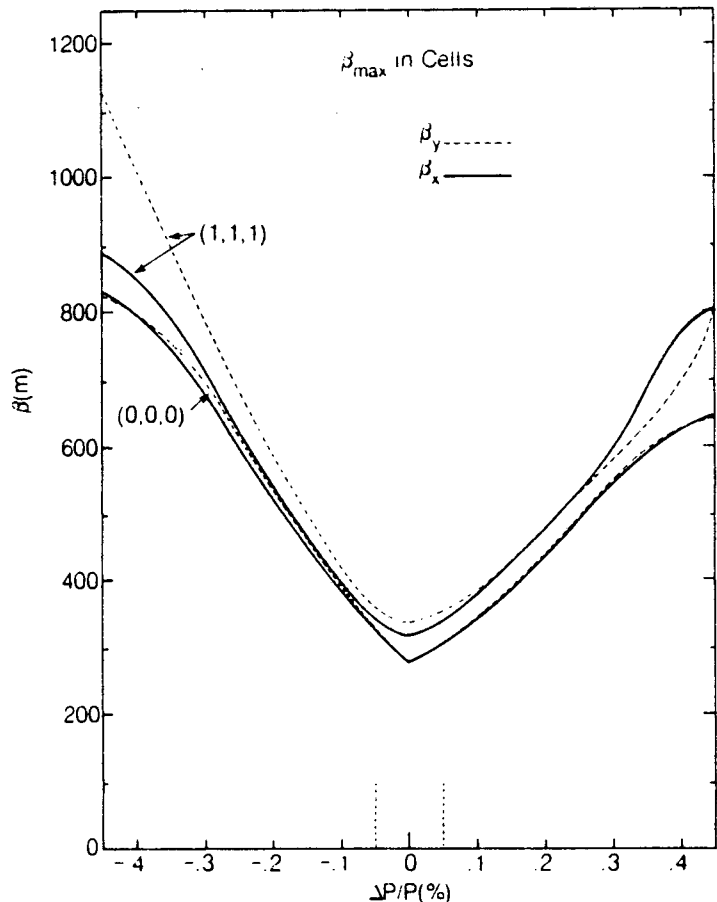


Fig. 1. Maximum beta values in the cells vs. momentum.

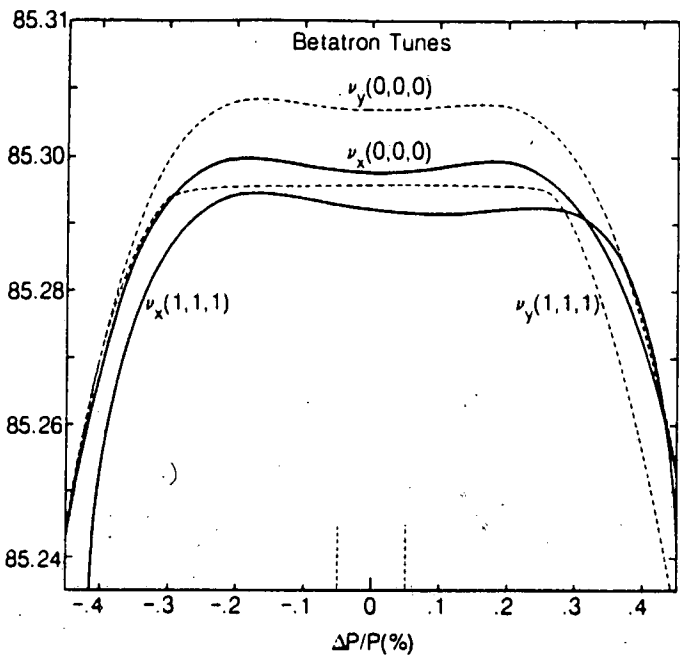


Fig. 2. Momentum dependence of the tunes for the perfect machine (0,0,0) and the machine with all multipole and closed orbit errors (1,1,1).

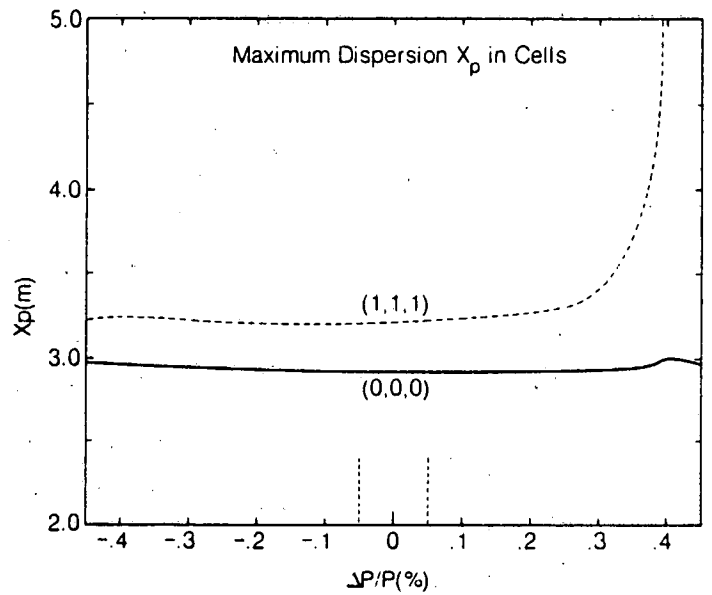


Fig. 3. Maximum dispersion values in the cells vs. momentum.

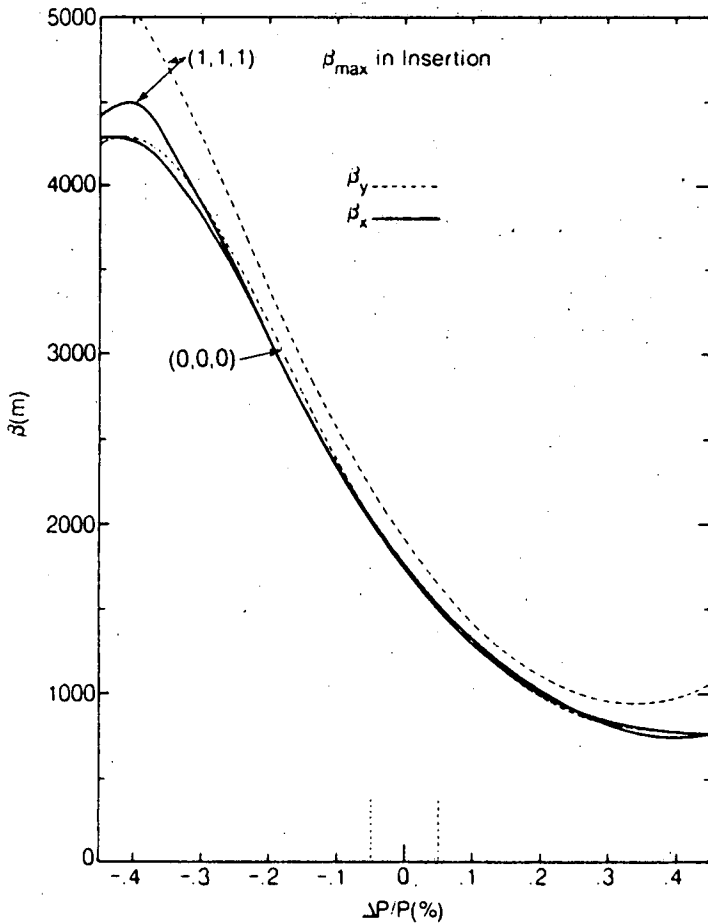


Fig. 4. Maximum beta values in the insertions vs. momentum.

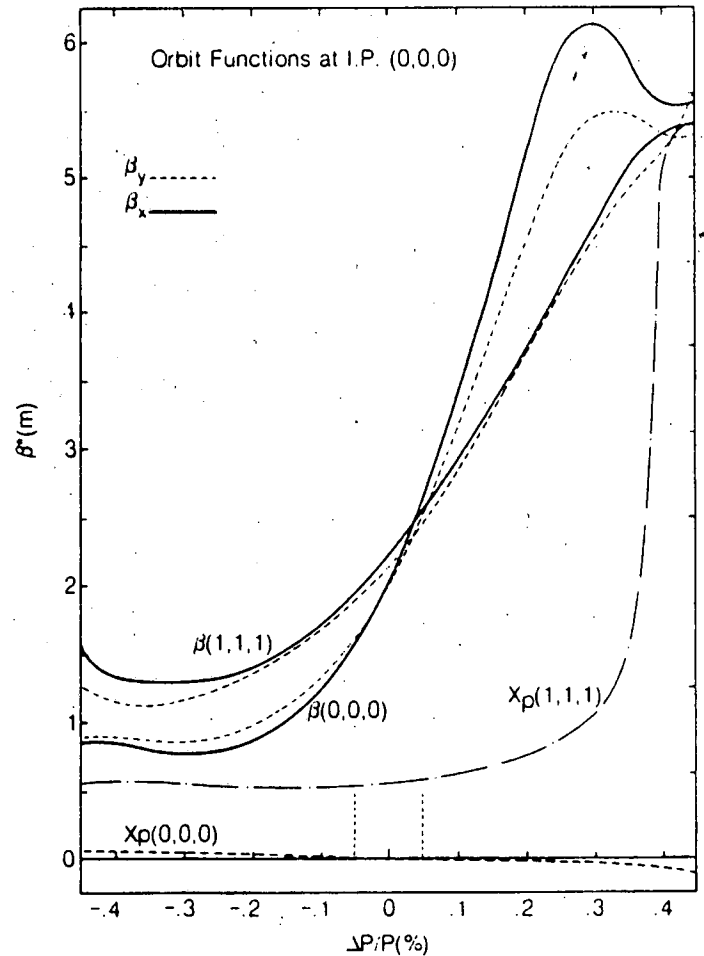


Fig. 5. Interaction point beta and dispersion values vs. momentum.

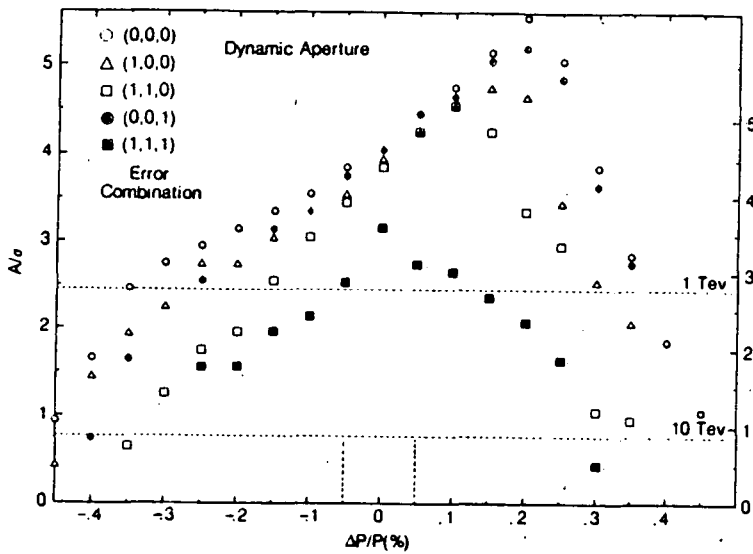


Fig. 6. Dynamic aperture for five error combinations from 200 turn runs.

The amplitude interval used was 0.1σ at 1 TeV, corresponding to a normalized emittance $\epsilon_n = 6\pi\gamma\sigma/\beta = 30\pi$ mm-mrad. Fig. 6 summarizes the stability limits for the five error combinations. All of the runs of Fig. 6 were of 200 turns duration. The dotted line at $A/\sigma = 2.44$ represents the amplitude required for a beam injected at 1 TeV, that at 0.79 represents 10 TeV.

Thus it appears that with all errors present at the assumed strengths (black squares) one could not safely inject at 1 TeV. It might be necessary to inject with a modified optics, and go at higher energy to the low- β configuration. However, with b_1 and b_2 compensated (white squares), injection into the experimental configuration may be possible.

In order to learn if runs of such limited length were reliable we compared runs of different durations. In Fig. 7 each symbol represents the stability limit deduced from runs of a specified number of turns. The upper points, connected with a dashed line, represent the perfect machine (0,0,0), while all those below the dashed line represent the case (1,1,1) - all errors. The convergence of the (0,0,0) points gives confidence that the true dynamic aperture may have been found for this case. At first sight the scatter of the (1,1,1) points is alarming, however most of the points for 200, 400, and 800 turns agree rather well.

The computer study only provides information on the short term behavior. It gives indications on the effect of chromatic aberrations and phase space distortions; it also provides a ground for comparison among possible SSC lattices, tunes, and magnet designs and helps to set tolerances. The long term behavior, typical of storage rings, is affected by time dependent phenomena like synchrotron oscillations, power supply ripple, noise, etc. All these effects are difficult to simulate with a computer in a realistic way because of the large amount of computer time required, effect of rounding off errors, etc. We must expect that in a real situation the dynamic aperture is smaller than the one computed by tracking studies over a few hundred turns. More work on the effect of magnetic imperfections, both theoretical and experimental, is required in order

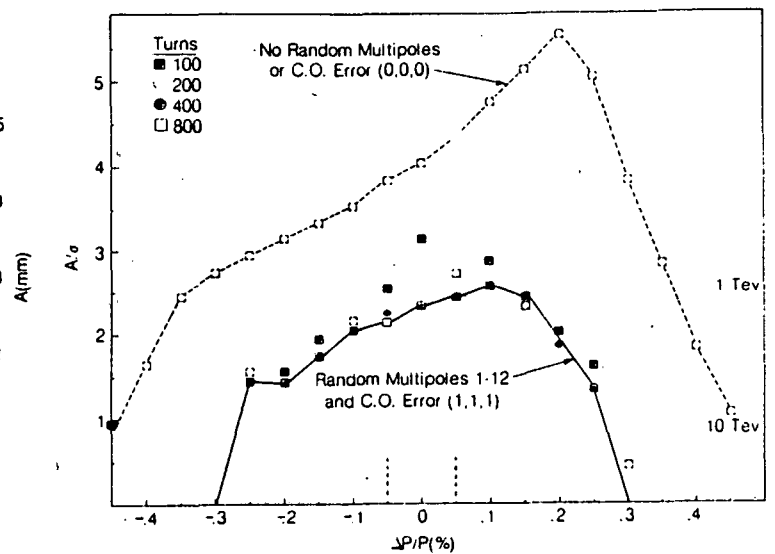


Fig. 7. Dynamic aperture for (0,0,0) and (1,1,1) machines as deduced from runs of different length.

to be able to confidently predict the performance of the beam in the SSC.

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