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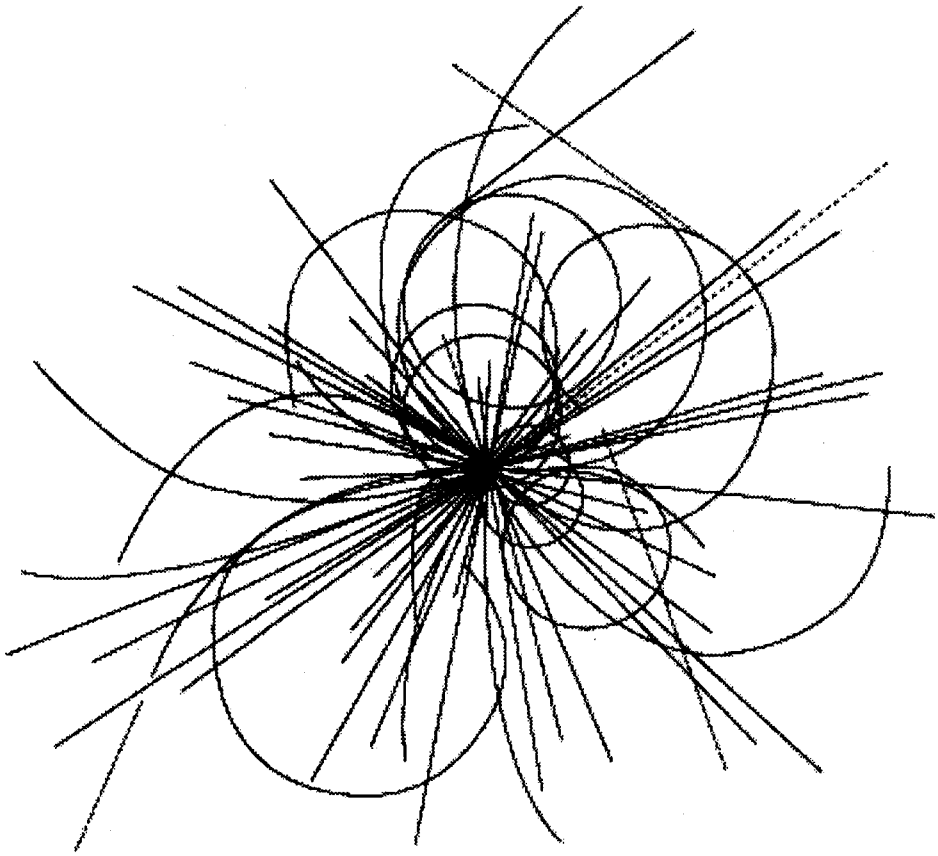

Superconducting Super Collider Laboratory

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Abstract

Computer simulations are made to study the decoherence of beam oscillations in the SSC collider in the presence of head-on beam-beam interaction. It is found that the decoherence time due to beam-beam tune spread is around 0.1 second, about six times shorter than a theoretical estimate made previously.

I. INTRODUCTION

In the SSC collider, there exist many external circumstances in which the centroid of a circulating beam is displaced from the design orbit. If particle motions are linear, the displaced beam will undergo betatron oscillations as a whole (coherently) because all particles in the beam have the same tune, defined by the number of betatron oscillations in one revolution. However, nonlinearities in the machine can cause different particles to have different tunes, i. e., can generate a tune spread in the beam. When this is the case, the betatron motions of particles in a displaced beam will not be coherent, and the so-called phase mixing or decoherence results. Eventually, the phase space distribution of the beam will approach an equilibrium with the beam centroid returning to the design orbit,

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and the beam size (emittance) enlarged. For the SSC collider, the tune spread is primarily generated by the nonlinear beam-beam force experienced by the two counter-rotating beams when they collide in the interaction regions. In this paper, using the weak-strong model, we simulate the SSC beam-beam interaction in the two low-β IRs and estimate the decoherence time of an initially displaced beam in the presence of the beam-beam interaction.

We will consider only the head-on beam-beam interaction and ignore energy spread in the beam.

II. SIMULATION

Up to 10^5 particles were tracked in the four-dimensional phase space (X, X', Y, Y') using a linear lattice for the SSC collider. Three locations in the lattice have been considered (see Figure 1): the two interaction points IP1 and IP2, and the location M where measurement of the beam position is made. Table 1 lists the relevant lattice parameters at these three points. The initial values of X, X', Y, Y' were generated at the point M using Gaussian distributions with a normalized emittance of $\varepsilon_N = 1$ mm mrad. The horizontal rms beam size is $\sigma_x = 140$ μm at the point M. Once generated, the initial beam was shifted horizontally by an amount ΔX_0, i.e., for every particle $X_i \rightarrow X_i + \Delta X_0$. Three transfer matrices were then used to carry the particles once around the collider ring: from the point M through the interaction points IP1 and IP2, and back to the point M. Typically particles were tracked for 5000 turns. At the interaction points, particles were given kicks because of the Coulomb beam-beam force, so that their angles were changed to

$$X' \rightarrow X' + \Delta X', \quad Y' \rightarrow Y' + \Delta Y'. \tag{1}$$

The kicks, $\Delta X'$ and $\Delta Y'$, were calculated using the weak-strong model in which the beam under consideration is regarded "weak" and the counter-rotating beam, unperturbed by the weak beam, is regarded "strong." Assuming the particle distribution of the counter-rotating beam is a round Gaussian, the kicks are given by [1]

$$\begin{bmatrix} \Delta X' \\ \Delta Y' \end{bmatrix} = \frac{2N_b r_p}{\gamma_p} \frac{1}{X^2 + Y^2} \left(1 - \exp\left(-\frac{X^2 + Y^2}{2\sigma^2} \right) \right) \begin{bmatrix} X \\ Y \end{bmatrix}, \tag{2}$$

where N_b is the number of particles in a bunch of the strong beam, r_p the classical proton radius, γ_p the Lorentz relativistic factor of a 20 TeV proton, and σ the rms

beam size at the low-β IPs. We have used $N_b = 0.8 \times 10^{10}$ and $\sigma = 5\ \mu m$ according to the SSC baseline design.

Table 1. Lattice parameters at locations IP1, IP2 and M.

S: path length; α, β: usual Courant-Snyder parameters; Q_x, Q_y: tune advances.

The total tune advances in one revolution are: $\nu_x = 123.285$ and $\nu_y = 122.265$.

	IP1	IP2	M
S	36 947.925 m	39 467.925 m	86 525.550 m
α_x	−0.003	−0.015	0.115
β_x	0.501 m	0.502 m	427.477 m
α_y	−0.024	0.001	−0.495
β_y	0.505 m	0.493 m	533.929 m
Q_x	52.022	56.275	122.735
Q_y	51.138	55.385	121.753

After each turn, at the point M, we calculated the beam centroid in phase space

$$X_c = \frac{1}{N}\sum_{i=1}^{N} X_i\ , \qquad X_c' = \frac{1}{N}\sum_{i=1}^{N} X_i'\ , \tag{3}$$

and the beam emittance relative to the beam centroid

$$\hat{\varepsilon} = \frac{\pi}{N}\sum_{i=1}^{N} (\gamma\hat{X}_i^2 + 2\alpha\hat{X}_i\hat{X}_i' + \beta\hat{X}_i'^2), \tag{4}$$

where $\hat{X}_i = X_i - X_c$, $\hat{X}_i' = X_i' - X_c'$, $\gamma = (1 + \alpha^2)/\beta$, and N is the number of particles being tracked (up to 10^5 particles). As we will see below, this relative-to-centroid beam emittance will grow and reach a maximal value in the decoherence process. Hence its growth profile is used in the following to characterize the speed of the decoherence process.

III. RESULTS

To illustrate the decoherent process due to the beam-beam interaction, we show in Figure 2 the phase space distributions of the beam at 1000, 2000, and 5000 turns after a horizontal displacement of $\Delta X_0 = 500\ \mu m$. As the beam decoheres, its

centroid position X_c oscillates with decreasing amplitude. This is illustrated in Figure 3 for an initial displacement of $\Delta X_0 = 50\ \mu m$. The centroid position eventually settles around zero (the design orbit) indicating the beam has reached an equilibrium. The time evolution of the beam emittance $\hat{\varepsilon}$ for the case of $\Delta X_0 = 50\ \mu m$ is shown in Figure 4. Here we see $\hat{\varepsilon}$ increases monotonously (on average) and finally approaches a steady-state value indicating again the beam has reached an equilibrium. As discussed earlier, phase mixing of particles due to the tune spread generated by the beam-beam interaction has contributed in establishing a new equilibrium of the beam.

We found that the growth profile of the beam emittance $\hat{\varepsilon}$ could be fitted to the following form:

$$\hat{\varepsilon} = A - B \exp\left(-t^2/2\sigma_d^2\right). \tag{5}$$

The value of σ_d obtained in the fit can be regarded as a measure of the speed of decoherence and is defined in this paper as the decoherence time. Figure 5 shows the fits for two cases: one with an initial beam displacement of $\Delta X_0 = 50\ \mu m$ and one with $\Delta X_0 = 300\ \mu m$. The decoherence times were found to be $\sigma_d = 0.112$ second (381 turns) in the first case and $\sigma_d = 0.132$ second (449 turns) in the second case. The dependence of the decoherence time on the initial beam displacement is shown in Figure 6. It appears that the decoherence time remains fairly constant for small beam displacements and increases rapidly when the beam displacement exceeds $\Delta X_0 \approx 1.5\sigma$.

IV. SUMMARY

Using computer simulation we have found that in the presence of the head-on beam-beam interaction in the SSC low-β IRs, the decoherence time of small beam oscillations is ~ 0.1 sec. This is about six times shorter than the theoretical estimate made in [2]. After we pointed out the discrepancy, a more careful theoretical calculation [3] showed good agreement with our simulation.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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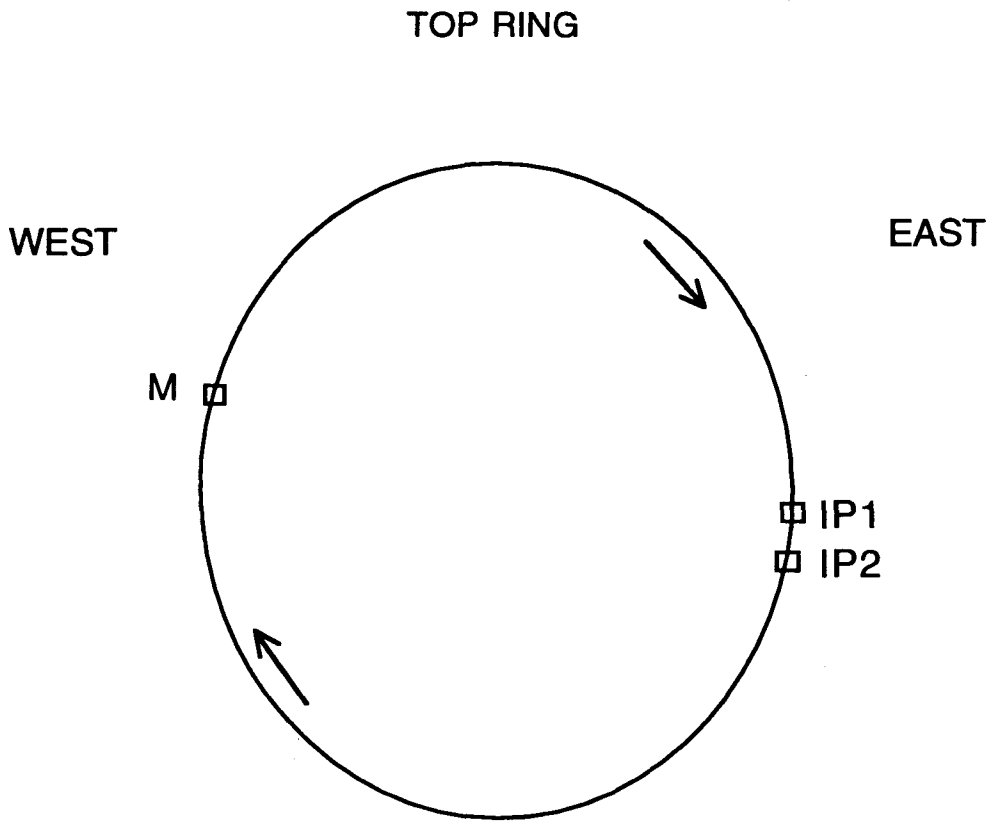


Figure 1. Schematic diagram of the SSC collider ring used for simulation. IP1 and IP2 – interaction points, M – measurement position.

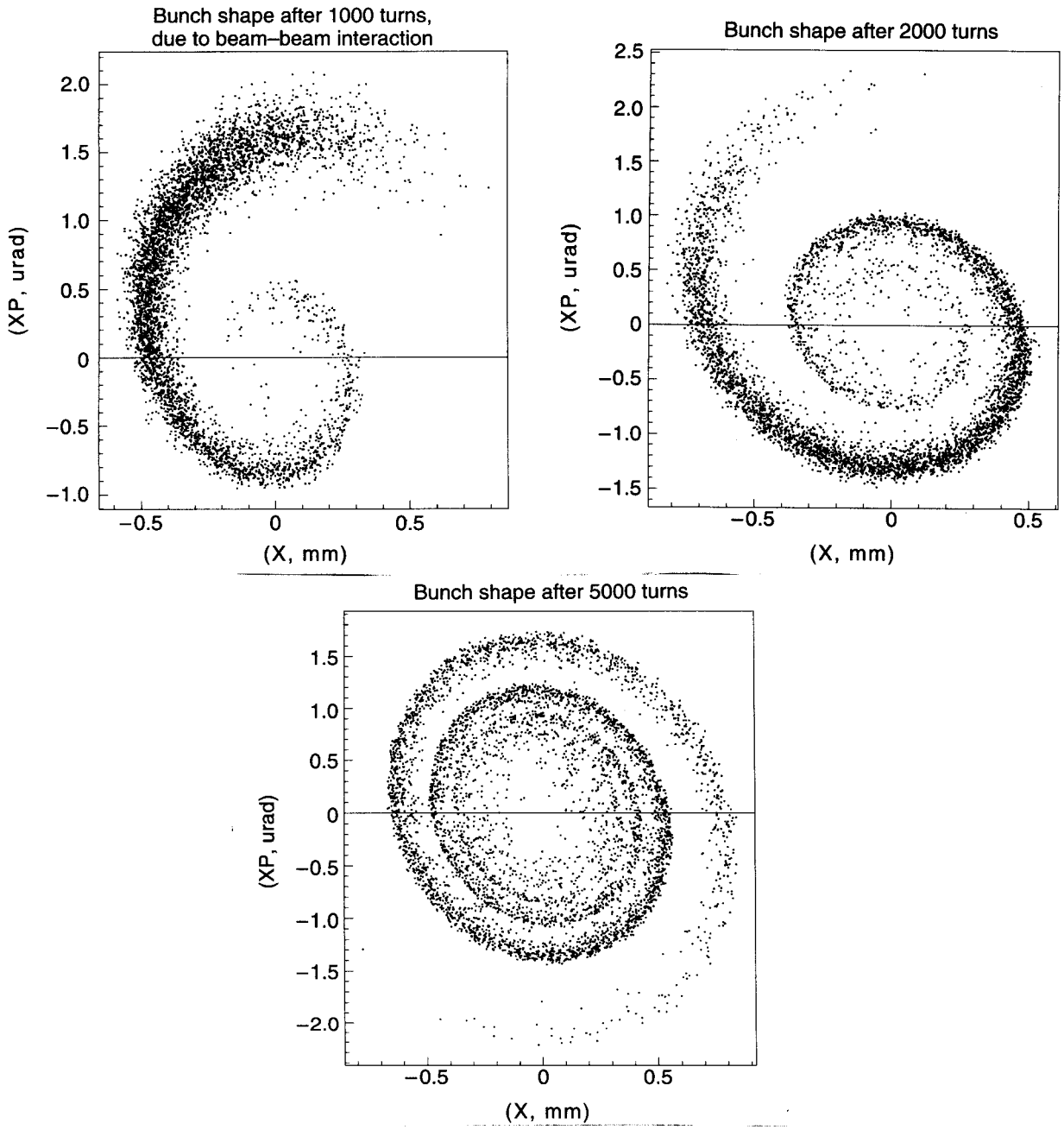


Figure 2. Distributions of the beam in phase space after a horizontal displacement of $\Delta X_0 = 500\ \mu m$. (a) At 1000 turns. (b) At 2000 turns. (c) At 5000 turns.

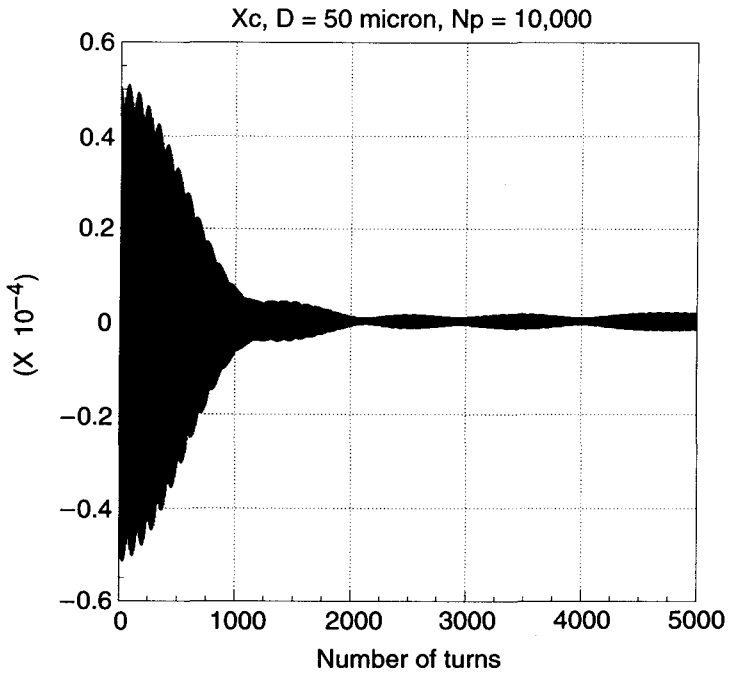


Figure 3. Beam centroid oscillations after an initial 50 μm beam displacement at the point M.

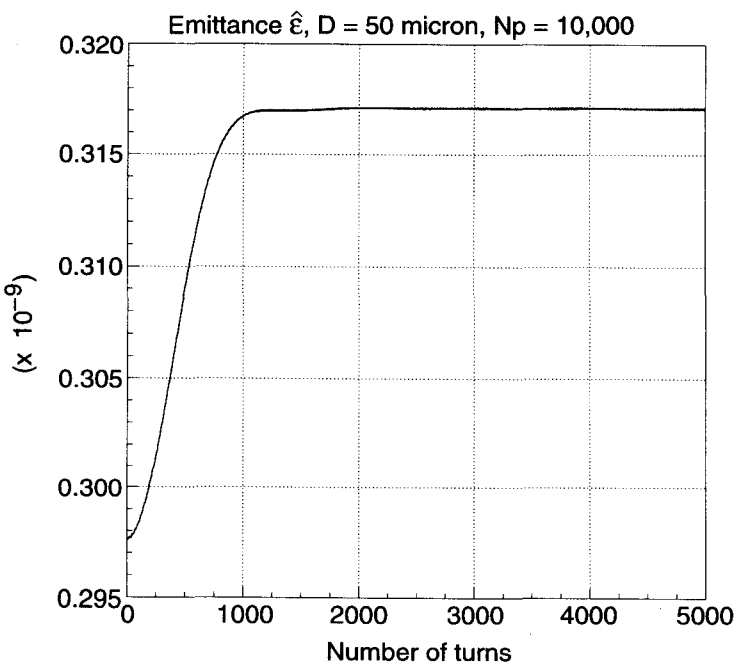
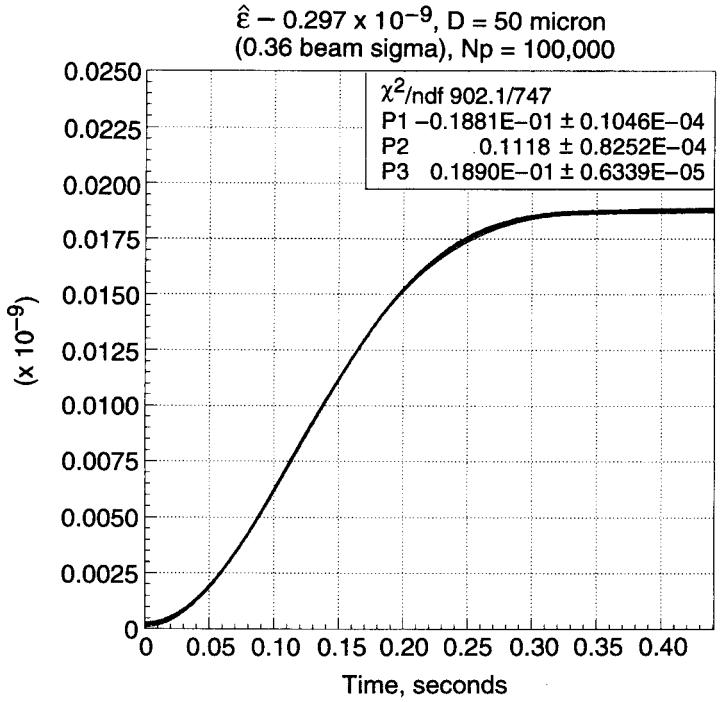


Figure 4. Relative-to-centroid beam emittance versus turn number for an initial beam displacement of 50 μm.



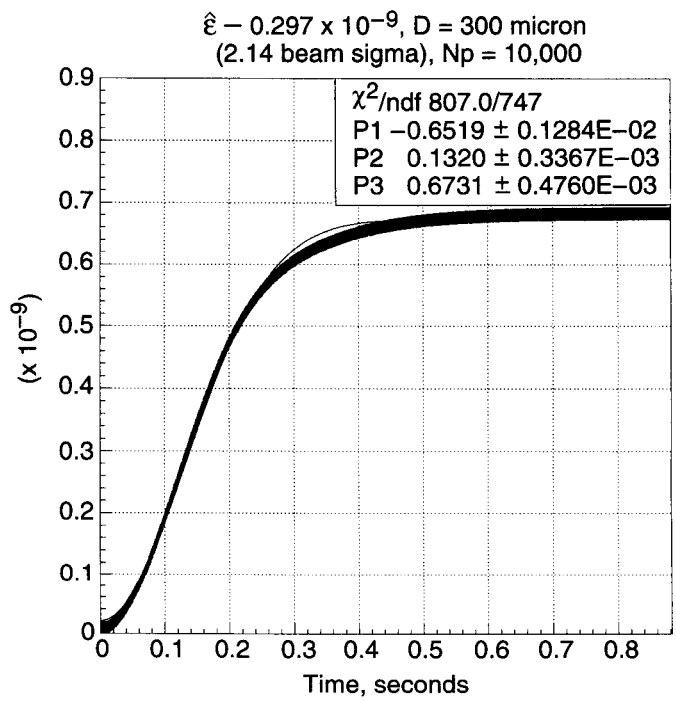


Figure 5. Fits of beam emittance growth as shown in Fig. 4 by a Gaussian form plus a constant term. (a) $\Delta X_0 = 50\ \mu m$. The decoherence time is 0.112 second. (b) $\Delta X_0 = 300\ \mu m$. The decoherence time is 0.132 second.

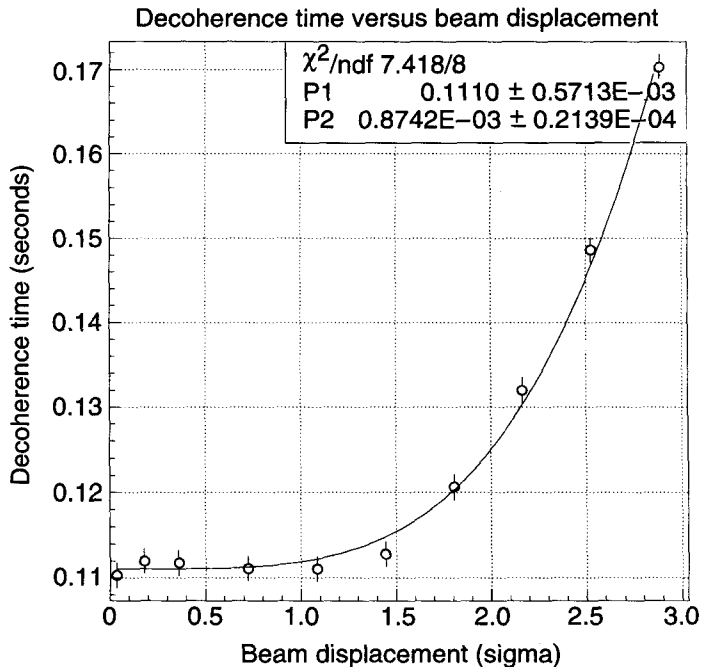


Figure 6. Dependence of the decoherence time on the amplitude of initial beam oscillations. The curve is a polynomial fit.