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Simulation of U-5 Prototype Undulator Effects on the Beam Dynamics

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Abstract

The APS prototype undulator U-5 has been installed at NSLS VUV ring. Its effects on the beam behaviour have been simulated with tracking codes TEAPOT and RACETRACK. The tune shift, the distortion of betatron function, the chromaticity, the transverse coupling, and some of the amplitude-dependent effects on the VUV ring have been compared and are presented in this paper.

INTRODUCTION

The U-5 undulator is a prototype insertion device for the Advanced Photon Source (APS) storage ring. It is a planar permanent magnet undulator with a period of $\lambda = 7.5$ cm, maximum field $B_0 = 0.46$ T at a minimum gap of 34 mm; the number of period is 27.5, so the length of the device is 206 cm. It has been installed in a straight section of the National Synchrotron Light Source's VUV ring. The VUV ring is a fourfold symmetric 750 MeV storage ring. There are four straight sections in the ring. Two straight sections are free for insertion devices. The vertical magnetic field of a insertion device can be approximated[1]:

$$B_y = B_0 cosh(k_x x) cosh(k_y y) cos(kz) \tag{1}$$

with

$$k^2 = k_x^2 + k_y^2 = \left(\frac{2\pi}{\lambda}\right)^2 \tag{2}$$

where λ is the period length of the insertion device and B_0 is its magnet field. If we assume that the magnet field of the insertion device is uniform in the x-direction, i. e. $k_x = 0$, then the equation of motion of the electron beam in the vertical plane becomes[2] :

$$y'' = -\left(\frac{y}{2\rho^2} + \frac{k^2 y^3}{3\rho^2}\right) \tag{3}$$

where ρ is the bending radius of the beam with respect to the peak field at the center of the undulator. The first term of equation (3) produces a linear focusing on the beam like

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a quadrupole. Its strength is proportional to the length of the device and to the square of the field. The second term is an octupole-like component which gives the beam a strong nonlinear effect. In addition to these inherent components, the measured magnet fields of the undulator has about a 100 G/cm integrated sextupole component and a 10 G skew quadrupole component. All these fields were considered in the simulations. The new RACETRACK (version 4) has included the insertion device function[3] which integrates the equations of motion. In TEAPOT[4] we simulate the full length of the undulator with four quadrupole magnets. The nonlinear part is modeled as a multipole in the middle point along the undulator; the skew quadrupole components are included in the tilt of the undulator quadrupole component.

SIMULATION RESULTS

1) Tune Shift

The most sensitive and important effect of the undulator on the beam is the tune shift. The vertical tune shift caused by the undulator is proportional to the undulator field as shown in Fig. 1. The simulation results from both codes are quite close to the measured data as shown in Fig. 1.

2) Betatron Function Distortion

The distortion of vertical beta function caused by the undulator is shown in Fig. 2. The relationship of the beta distortion to the undulator field is shown in Fig. 3. No measured data can be compared to the simulation, but they are both close to the estimated data:

$$\frac{\Delta\beta_y}{\beta_y} = \frac{\beta_y L_{id}}{4\rho^2 sin(2\pi\nu_y)} = 9.7\%. \tag{4}$$

The simulation results of the vertical tune shift and betatron function distortion caused by the U-5 undulator are listed below.

Table 1: The tune shift and distortion of β function caused by U-5 undulator in VUV ring

B_0 (T)	$\Delta\nu_y$		$\Delta\beta_y/\beta_y$ (%)	
	1	2	1	2
0.46	0.0144	0.0137	8.64	9.53
0.345	0.0082	0.0078	4.85	5.41
0.23	0.0037	0.0034	2.15	2.46
0.115	0.0009	0.0008	0.53	0.69

1. simulation result from TEAPOT
2. simulation result from RACETRACK

The beta function in Table 1 is compared at the center of the straight section in TEAPOT and at the maximum beta position in RACETRACK. The tune has been readjusted to the original value in each comparision of betatron function distortion.

3) The Chromaticity

The measured U-5 undulator field has an integrated sextupole component of about 100 G/cm. The chromaticity change caused by this error component is very small. Figure 4 shows the tune shift *versus* the momentum change with and without the undulator. Since

$$\Delta\nu = \xi\frac{\Delta p}{p} \quad , \tag{5}$$

the tune shift caused by chromaticity is propotional to the momentum variation. The simulation results show that the sextupole component of the undulator changes the chromaticity just a little. The chromaticities are ξ_y = -2.7993 and ξ_x = -3.476 without the undulator. The vertical chromaticity changes to ξ_y = -2.7647 with the U-5 device at the peak field. The horizontal chromaticity is actually unchanged at the same time.

4) The Coupling Effect

The measured undulator magnetic field carries a skew quadrupole component of about 10 G. A skew qudrupole will cause coupling between horizontal and vertical betatron motions of the beam. A strong coupling may drive resonances of the type $m\nu_x+n\nu_y$=integer. Even far from a resonance a strong coupling will shorten beam lifetime by losing the particles from increased vertical amplitude. A moderate coupling also will lead to increased beam size which degrades the photon beam output. Fortunately, the coupling effects caused by this error component are quite small; however, they can still be seen in the horizontal tune spectrum of Fig. 5 and in the beating of the turn by turn amplitude of the beam (Fig. 6). All these coupling effects are more evident with larger amplitudes of the betatron oscillation.

5) Nonlinear Effects and Dynamic Aperture

The nonlinear effects of the undulator strongly depend on the betatron amplitude. The vertical phase space in Fig. 7 shows that the chaotic layer will appear in phase space with the larger amplitude. The similar amplitude-dependent effect can also be seen in Fig. 8 for beam smear. Figure 9 shows the tune shift vs the betatron amplitude which is the input value in simulation. The nonlinear effect of the undulator that is of greatest concern is reduction of the dynamic aperture. Figure 10 shows the reduction of dynamic aperture at the peak field of the device.

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[4] L. Schachinger et al., "Manual for the Program TEAPOT," SSC Central Design Group, August, 1991.

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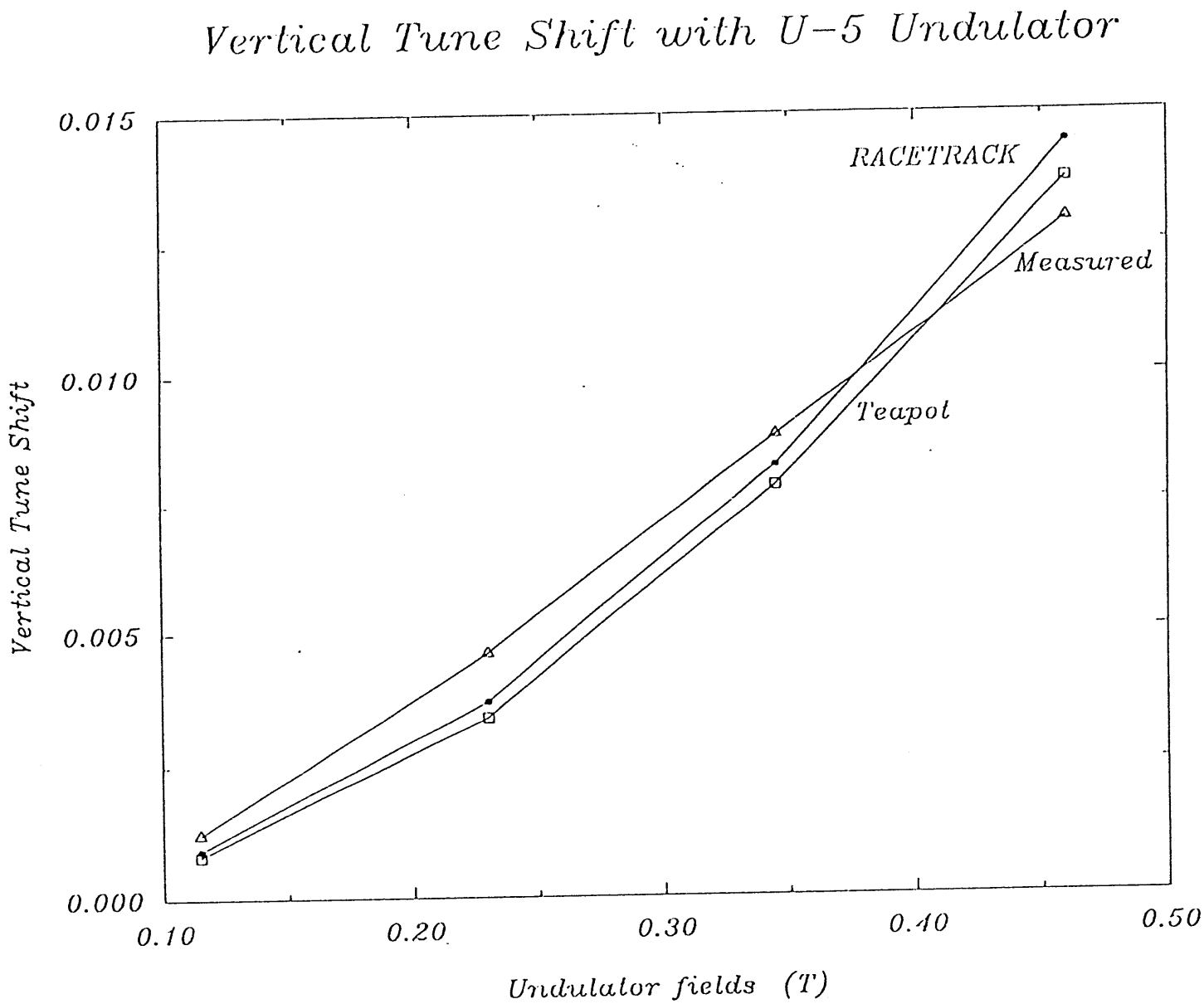


Fig. 1 The vertical tune shift with undulator field

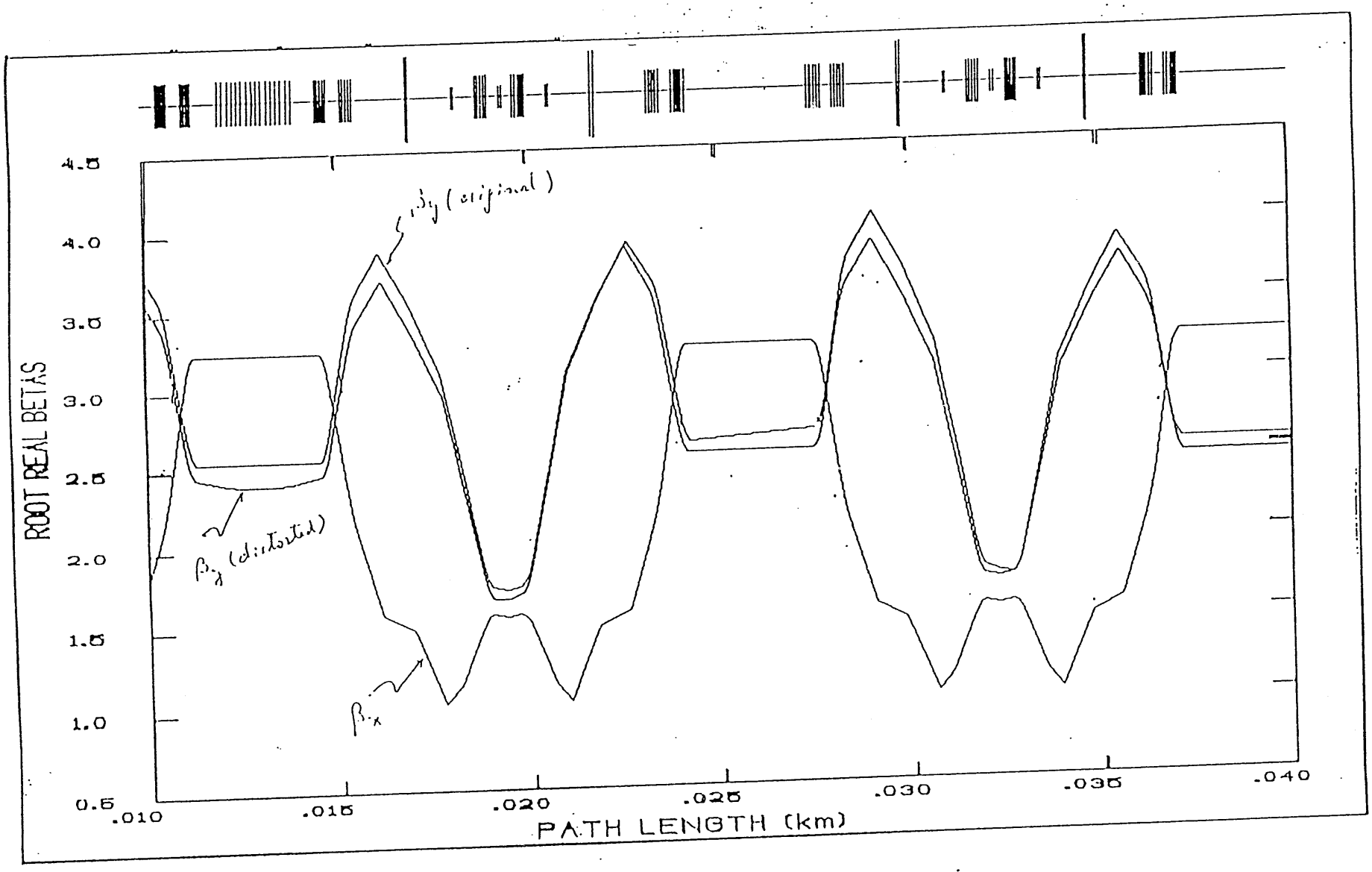


Fig. 2 The vertical betatron function distortion

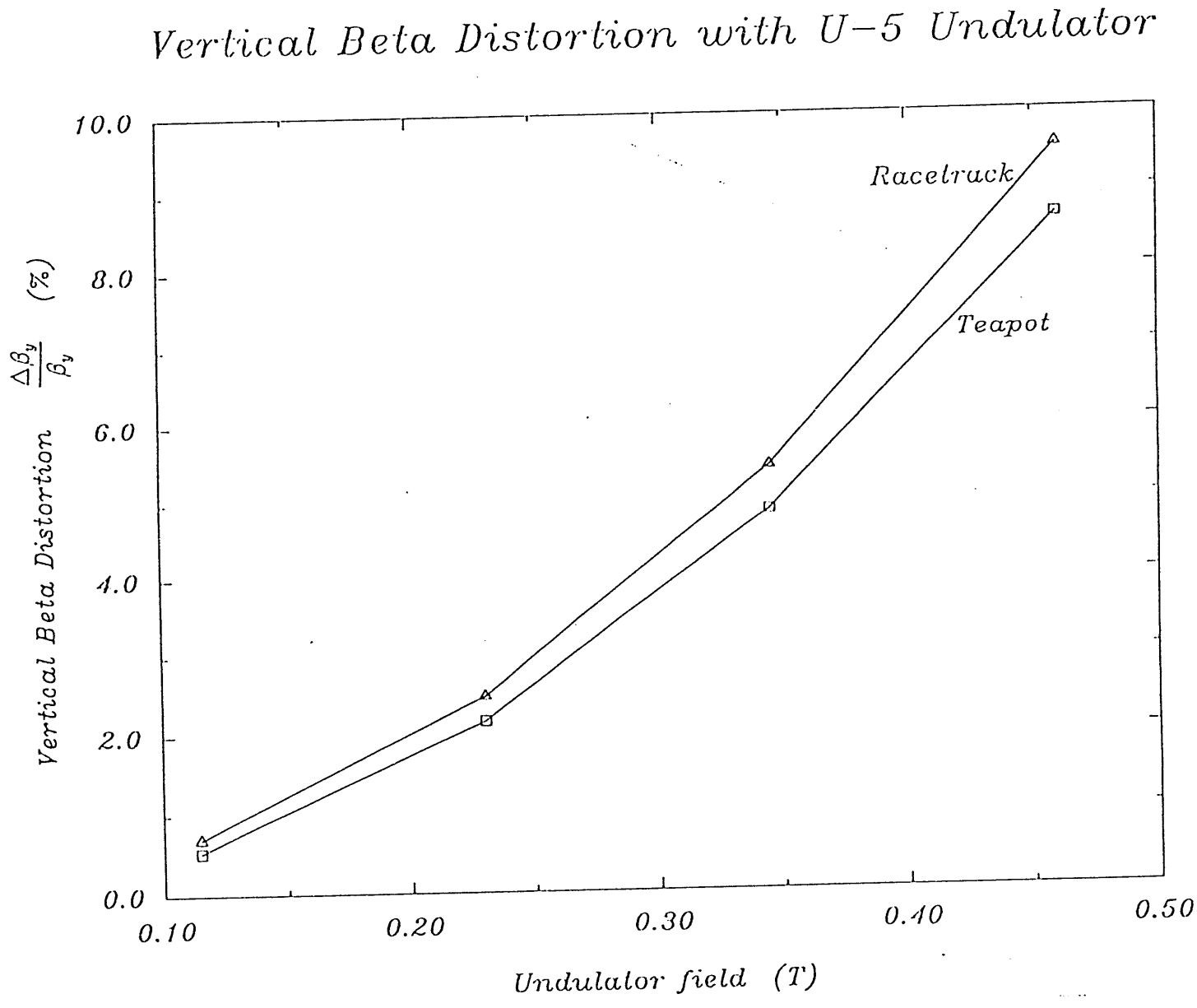


Fig. 3 The vertical betatron function distortion with the undulator field

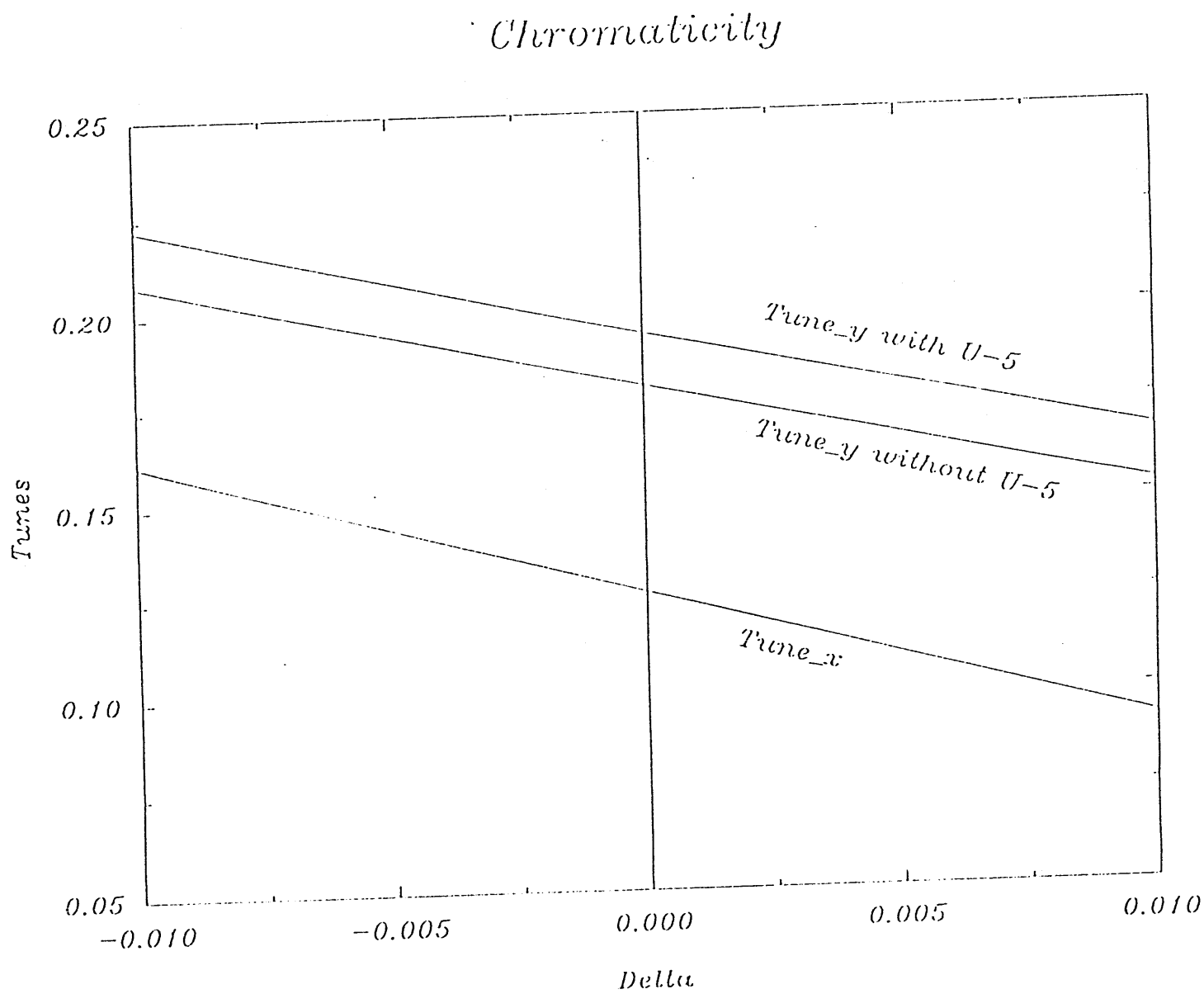


Fig. 4 The tune shift with the momentum change

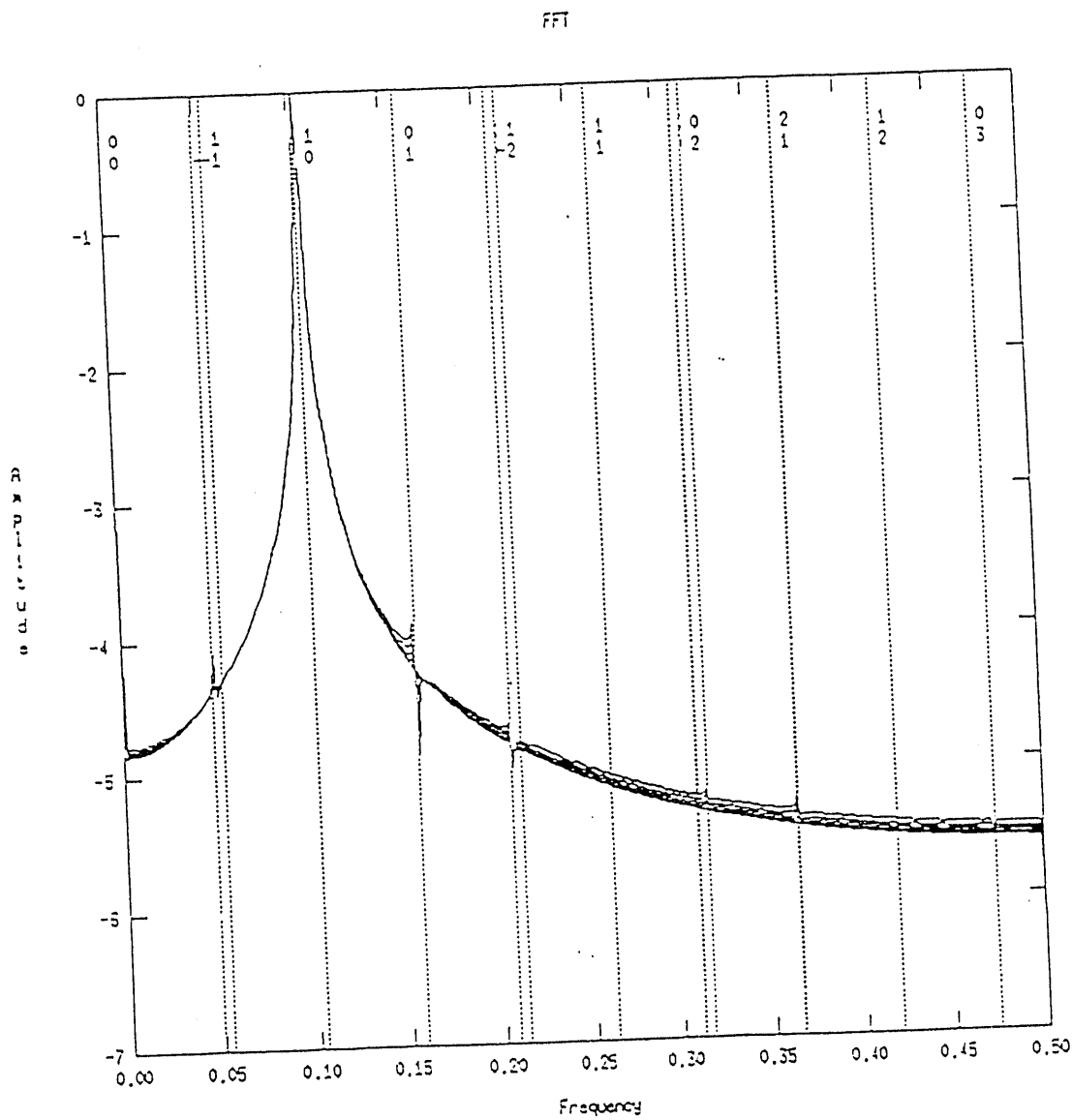
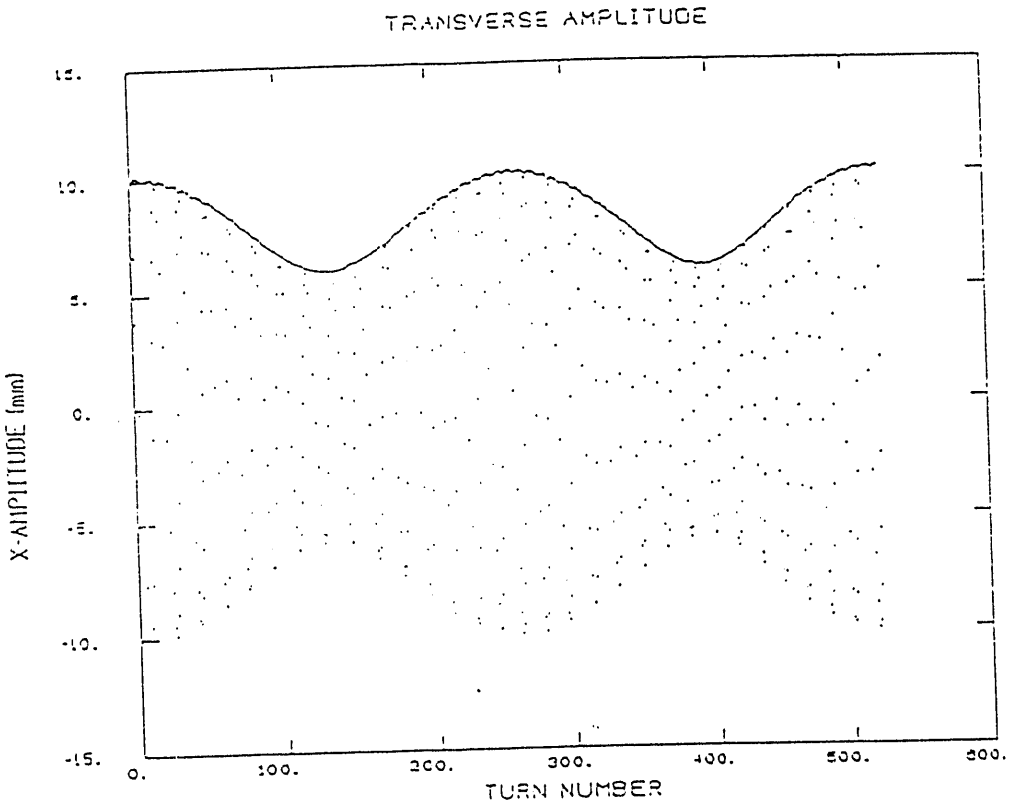


Fig. 5 The horizontal tune spectrum with coupling



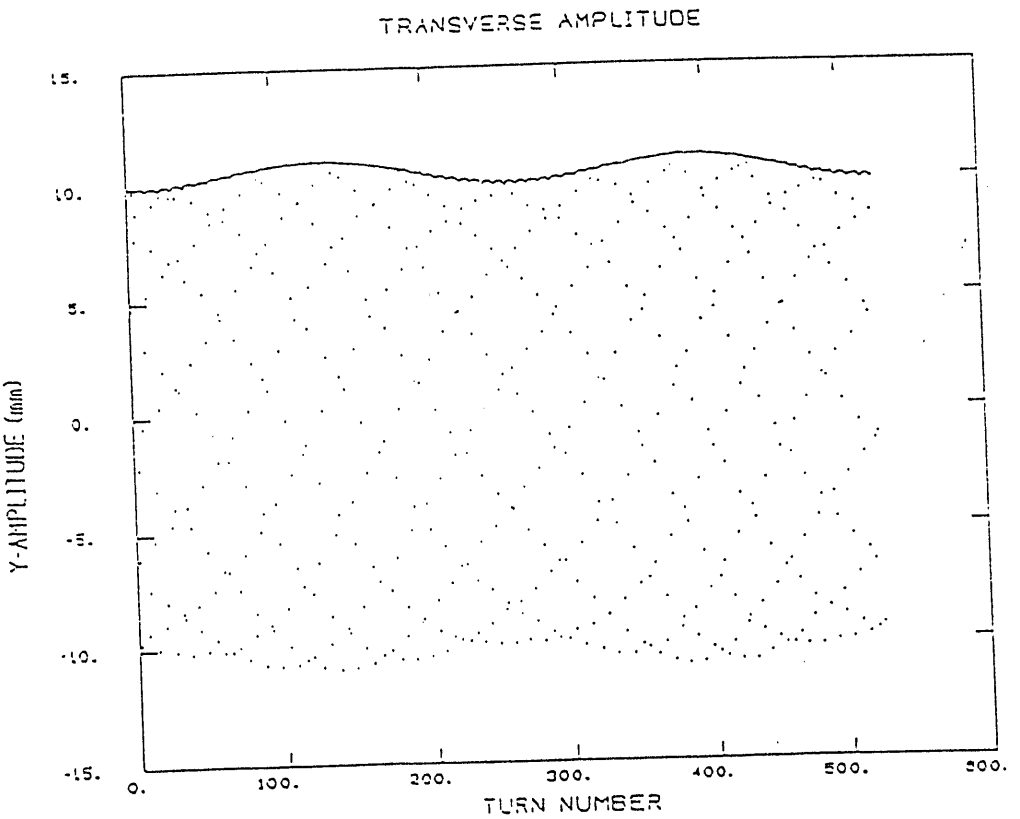


Fig. 6 The coupled betatron oscillation

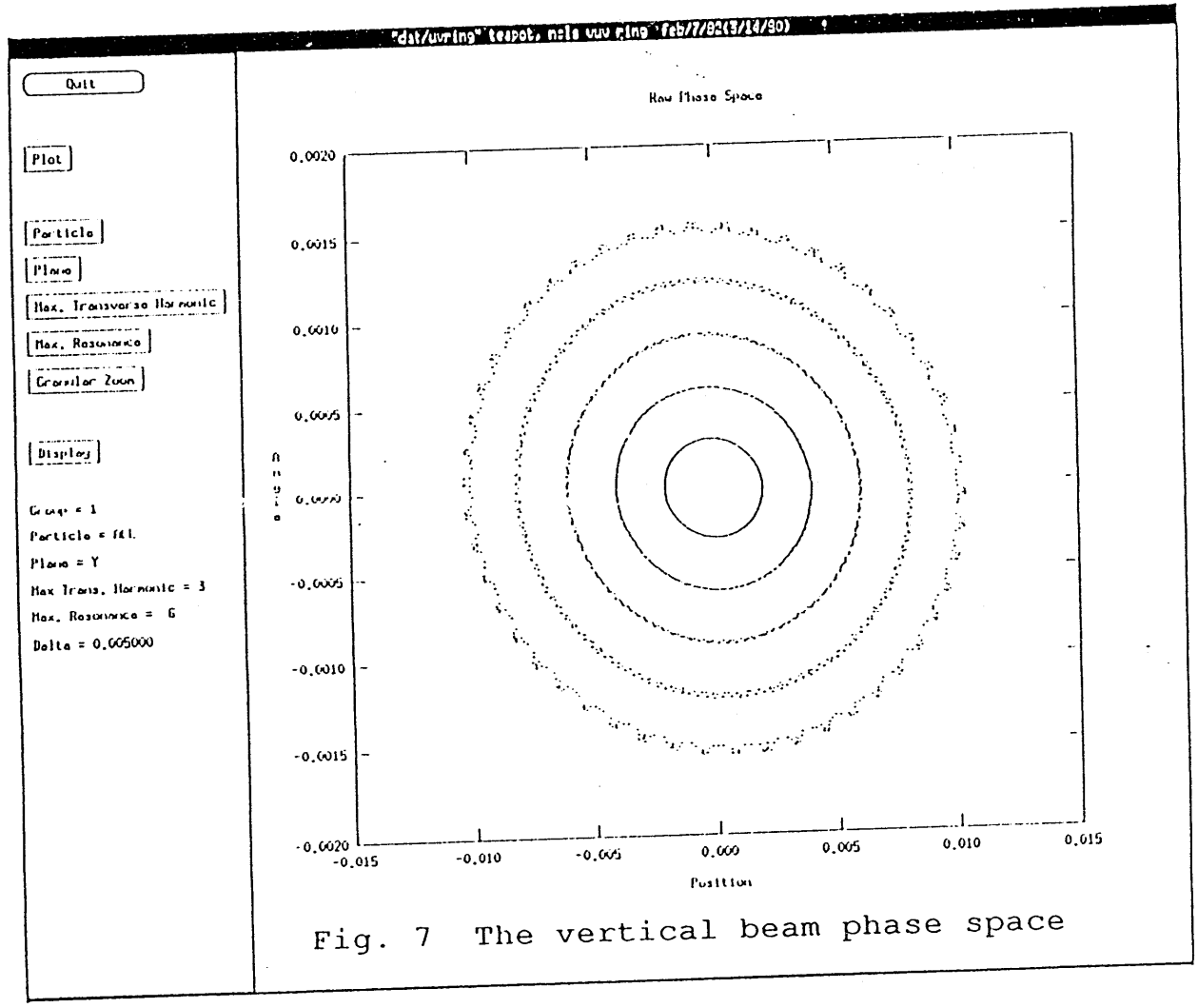


Fig. 7 The vertical beam phase space

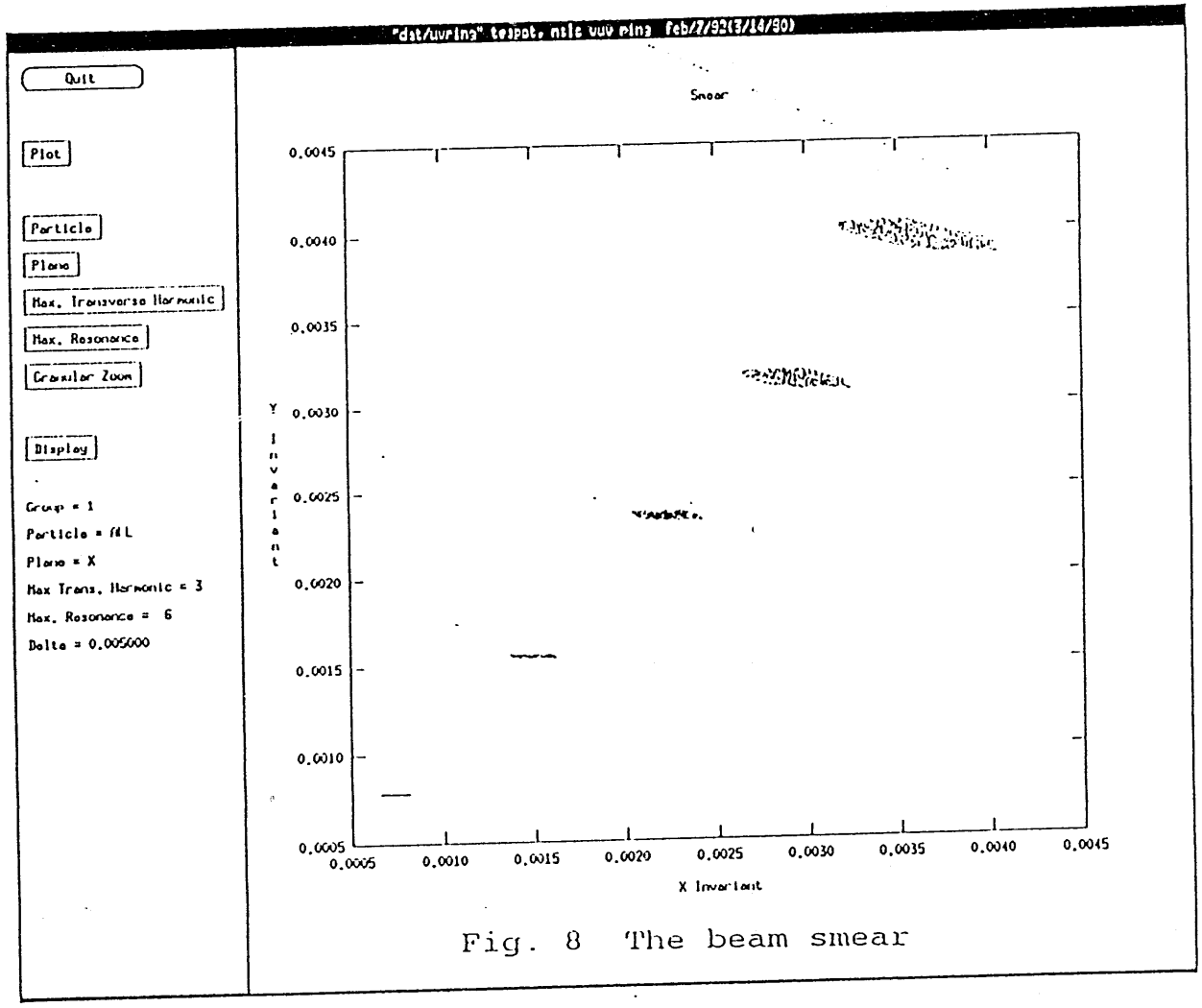


Fig. 8 The beam smear

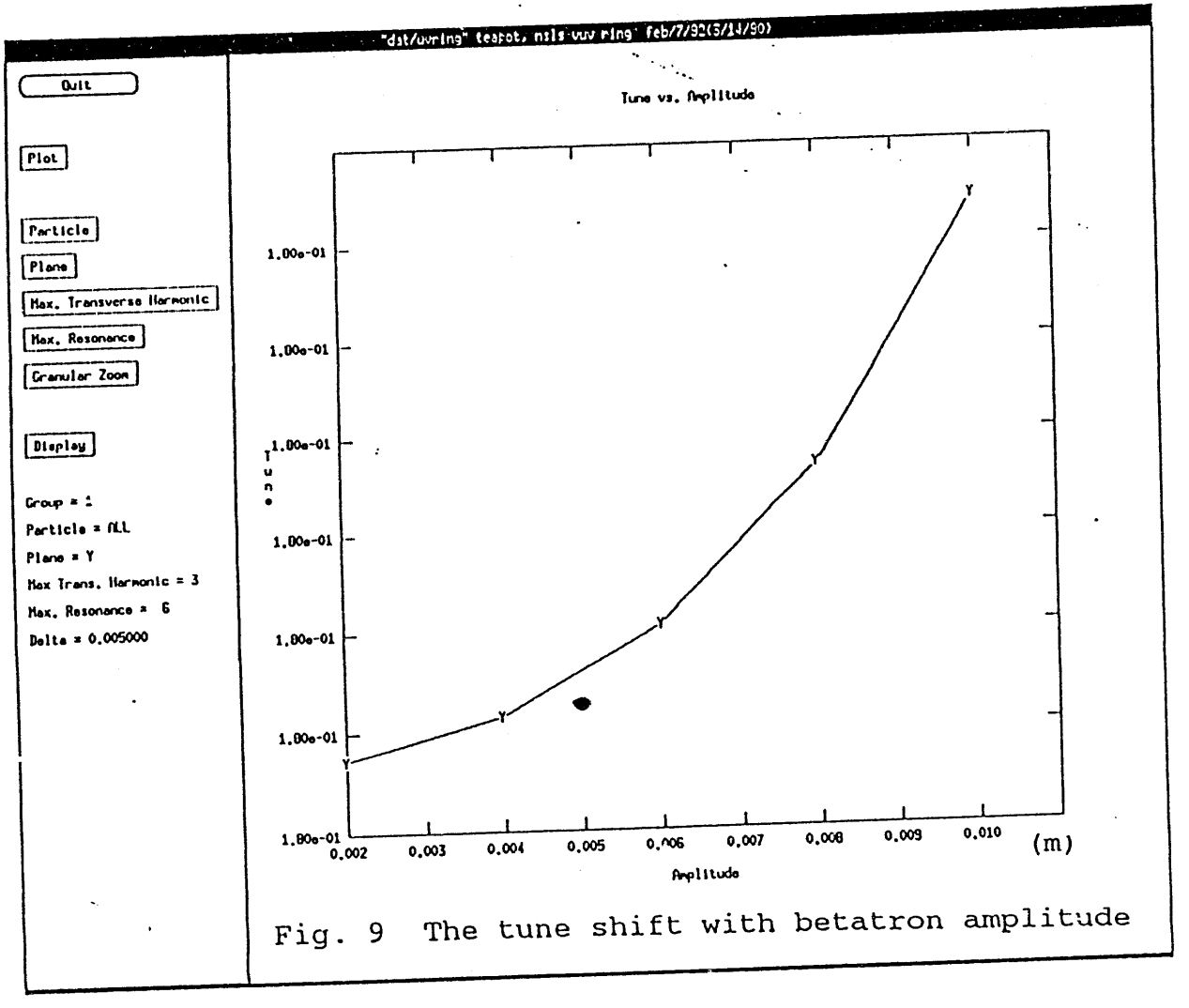


Fig. 9 The tune shift with betatron amplitude

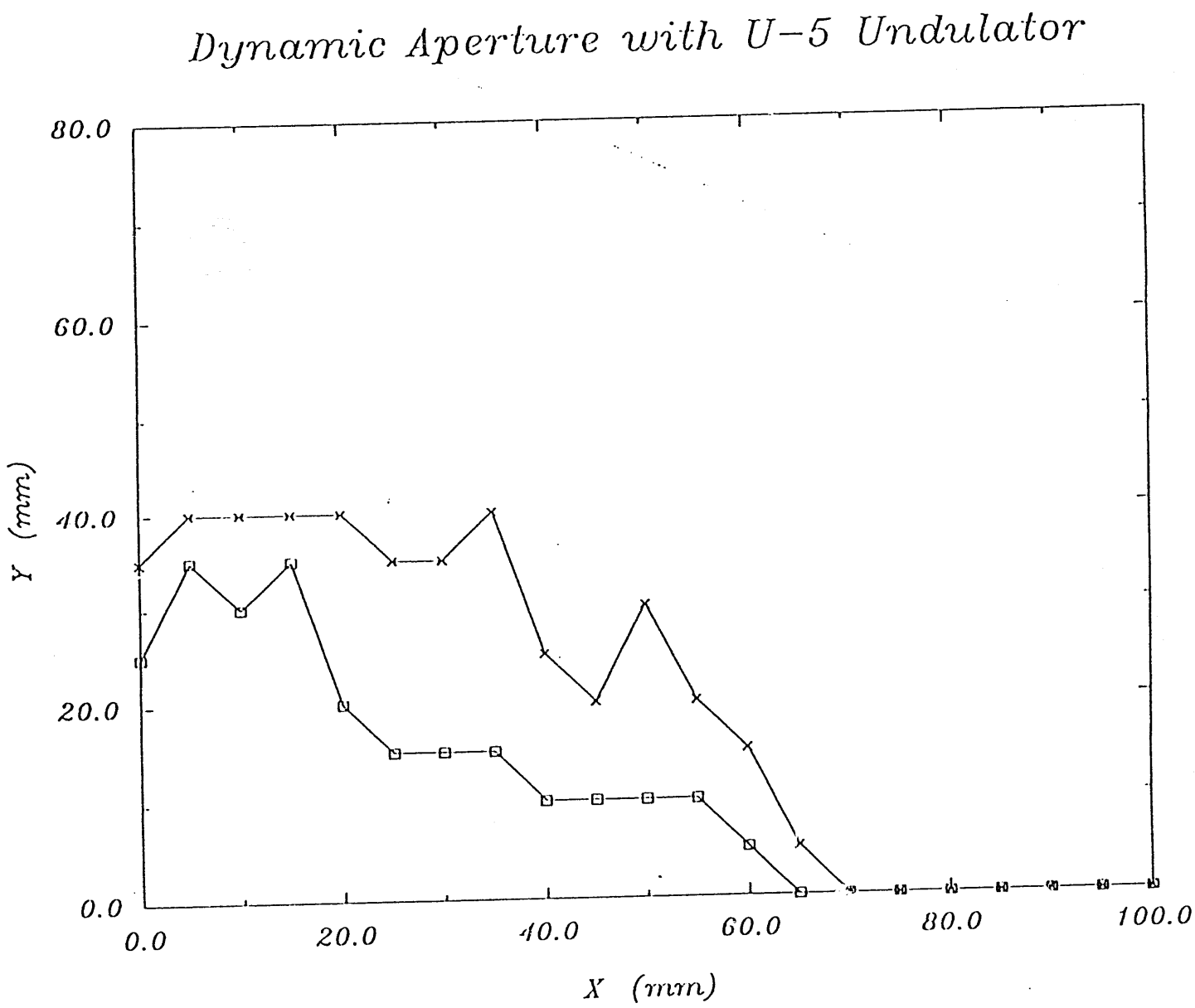


Fig. 10 Dynamic aperture with the influence of U-5 undulator

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