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On Asymmetric Collisions with Large Disruption Parameters

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Abstract

Collisions between a weak electron bunch and a strong positron bunch are studied within a flat beam model. Electrons are tracked through the transverse space charge field of the positron bunch, and it is shown that positrons in a storage ring may remain stable after asymmetric collisions with a weak electron bunch in spite of large values of the electron disruption parameter. The plasma oscillations that affect collisions with large disruption parameters may be suppressed by properly matching the electrons.

Introduction

Recently B-factories have been proposed based on the asymmetric collisions of an electron beam from a linac with a positron beam accelerated and stored in a storage ring (SR) [1,2]. In practice, the average current in the linac is limited by the RF power, or by the beam breakup (BBU) instability. As a consequence, high luminosity may be achieved only with collisions where the disruption parameter for the electrons is very large but that for the positrons remains small. Compared to the symmetric collisions in storage rings where the disruption parameter is always small, a qualitatively new situation arises since the disrupted electron beam may be removed after the collision.

The disruption of the electron beam affects the kinematics of the collisions, creates a background problem in the detectors, and makes handling of the electron beam after collisions more difficult. These problems may be partially solved by shifting the interaction point (IP) to the end of the interaction region. However, the major problem is that the disrupted electron bunch affects the dynamics of the positrons, generating an orbit distortion and a tune spread. Hence, it should be carefully studied whether the positron beam in the SR remains stable after such a collision.

Here we give the results obtained with a simple model which indicate that the situation is not hopeless: positrons may remain stable, and high luminosity is achievable.

Model

Asymmetric collisions give preferable kinematics for analysis of the CP violation in B decays and also allow a relatively low energy electron beam. We choose the energy of the electron beam to be 3.5 GeV. Using still lower energy would increase the energy of the SR, the power consumed in the SR, and the emittance of the positron beam.

The main advantages of a superconducting linac are the low emittance of the electron beam and the low RF losses in the cavities. Large cavity apertures are possible, and, therefore, the transverse impedance is reduced. The principal limitation on the electron current in such a linac is given by the single bunch transverse beam break-up (BBU) instability. Simulations of the BBU instability [3] at CEBAF predict the emittance doubles for 2.2 psec parabolic bunches if

$$w_{total} * I_p \; = \; 2.74 \times 10^7 \;\; \mathrm{A\ V/pC\ cm^2} \qquad (1)$$

where I_p is the peak current, and w is the slope of the transverse wake field. The doubling threshold rapidly decreases with the bunch length. Therefore, we choose 2.2 psec bunch length of the CEBAF electron beam for the B-factory. The effective CEBAF impedance [4] gives the slope $w = 471.0\ \mathrm{kV/pC\,cm^2}$. Eq. (1) gives a doubling threshold of $N_e = 0.544 \times 10^9$. The dependence of the threshold current on the electron energy is very weak. The peak current cannot be increased by BNS (for Balakin, Novokhatsky, and Smirnov) phasing in the linac [5,6] to minimize the emittance degradation. The necessary phase offset is large, reducing the acceleration rate to unacceptable levels. Therefore, N_e is relatively small, and the disruption parameter for the positrons is small, $D_p \ll 1$.

If the transverse rms bunch sizes at the IP are matched, the luminosity expressed in terms of N_e and the electron disruption parameter D_e takes the form:

$$L = \frac{N_e f \gamma_e D_e}{8\pi r_0 \sigma_{pz}} \tag{2}$$

where

$$D_e = \frac{2 r_0 N_p \sigma_{pz}}{\gamma_e \sigma_{px} \sigma_{py}}. \tag{3}$$

The repetition rate f is limited by multibunch instabilities, power limitations, and the rise time of the kickers. Assuming $N_e = 0.5 \times 10^9$, $f \leq 20$ MHz, and $\gamma_e = 7.0 \times 10^3$, we obtain

$$L = \frac{10^{34}}{101.2} \frac{D_e}{(\sigma_{pz}/\text{mm})} \text{cm}^{-2}\text{sec}^{-1}. \tag{4}$$

Hence, for a positron bunch length σ_{pz} of the order of 1 mm, the desired luminosity $L = 10^{34}$ $\text{cm}^{-2}\text{sec}^{-1}$ may be achieved with a linac having CEBAF parameters only if $D_{ey} \simeq 100$. This is at least two orders of the magnitude larger than that usual for storage rings.

The positron disruption parameter

$$D_p = \frac{2 r_0 N_e \sigma_{ez}}{\sigma_{ex} \sigma_{ey} \gamma_p}, \tag{5}$$

is small because the number of electrons per bunch is about two orders of magnitude lower than that for positrons. In this case the disruption of the positron beam may be neglected in the first approximation. We consider for simplicity flat Gaussian bunches ($\sigma_x \gg \sigma_y$) with the longitudinal density ρ_z normalized to one.

The equation of motion in the y-plane for an electron is

$$\frac{d^2}{dz^2}\left(\frac{y}{\sigma_{py}}\right) + \frac{2D_e}{\sigma_{pz}} \rho_z^p(s_e + 2z) \int_0^{y/\sigma_{py}} dy e^{-y^2/2} = 0 \tag{6}$$

where s_e is the distance of an electron from the center of the electron bunch, positive in the direction of motion, and $z = vt$.

For small y Eq. (6) is the equation of plasma oscillations with frequency given by

$$k^2(z) = \frac{2D_e}{\sigma_{pz}} \rho_z^p(2z) \tag{7}$$

and the total number of oscillations during the collision is [7]

$$n_{osc} = \int_{-\infty}^{\infty} \frac{k dz}{2\pi} = 0.252\sqrt{D_e}. \tag{8}$$

For large electron disruption parameters the number of nodes increases. The positron bunch may be considered as a "transport line". The beta function of the line $1/k(z)$ is on average

$$\beta_{eff} = \left(\frac{1}{2\pi}\right)\left(\frac{2\sigma_{pz}}{n_{osc}}\right) = 1.26\frac{\sigma_{pz}}{\sqrt{D_e}}. \tag{9}$$

An example of trajectories found by numerical integration of Eq. (6) for $s_e = 0$ is given in Fig. 1 for zero initial emittance and the disruption parameter $D_e = 120$. The number of oscillations agrees with the estimate Eq. (8). The frequency of plasma oscillations rapidly decreases with the increasing amplitude $y_e(-\infty)$ as is clear from Eq. (6). Hence, decoherence of the oscillations might be expected. This is depicted in Fig. 2. Initial conditions for 100 trajectories were set at $z/\sigma_{pz} = -3.02$ from the IP. The initial conditions were generated randomly within an ellipse on the phase plane y, y' in such a way that the ellipse has transverse size σ_{py} and beam divergence $\sigma_{py}k(0)$ after free motion transformation to the IP. Three hundred steps were used to calculate each trajectory. Decoherence is explicit, but remnant nodes are retained as is clear from Fig. 3 where the transverse rms size of the electron beam is depicted along the IR.

The beam–beam tune shift for a positron located at distance s from the head of the positron beam depends on the local transverse size of the electron beam at distance $s/2$ from the head of the electron beam. The tune shift may be very large for positrons located at the nodes of the electron beam, and such positrons may become unstable. It is enough to have a single node to lose positrons since the synchrotron motion shuffles positrons along the bunch, and new positrons are continually pumped to the nodes where they are lost.

In addition to the tune shift, the kink instability and the synchrotron radiation during the collisions might be affected by the large disruption parameter. Transverse instability of positrons around the nodes generates a periodic perturbation of the longitudinal density in the positron bunch with the wave length $2\pi/k$:

$$\rho(z) = \rho_0[1 + \Delta\cos(kz)].$$

Because k^2 in the equation of motion for electrons depends on $\rho(2z)$, the linearized equation of motion takes the form typical for the parametric resonance:

$$y'' + k^2[1 + \Delta\cos(2kz)]y = 0$$

where $'$ denotes the derivative with respect to z. This induces the "kink instability" observed in simulations of the beam-beam interactions in storage rings. For the asymmetric scheme under consideration where the electron beam is dumped out after a collision and the plasma frequencies for positrons and electrons are very different, the kink instability should not cause a problem.

Synchrotron radiation is a serious problem for collisions with large D_e. The radius of curvature R for a trajectory $y(s)$ is

$$\frac{1}{R} = -y'' = \frac{2D_e\sigma_{py}}{\sigma_{pz}}\rho(2s)\int_0^{y/\sigma_{py}} dte^{-t^2/2}$$

Minimum R occurs when $y \geq \sigma_{py}$. The maximum energy loss during the collision is

$$\Delta E = \frac{2}{3}r_0\gamma_e^3 E_e \int ds(1/R)^2$$

where E_e is the electron energy. It is proportional to

$$\int ds(1/R)^2_{max} \simeq \left(\frac{D_e\sigma_{py}}{\sigma_{pz}}\right)^2\frac{\sqrt{\pi}}{2\sigma_{pz}}. \quad (10)$$

The variation in the invariant mass

$$\frac{\Delta M}{M} \simeq \frac{r_0}{3}\gamma_e^3\left(\frac{D_{ey}\sigma_{py}}{\sigma_{pz}}\right)^2\frac{\sqrt{\pi}}{2\sigma_{pz}}$$

is less than 0.5×10^{-3} if

$$\frac{D_{ey}\sigma_{py}}{\sigma_{pz}} < 4.2 \times 10^{-2}\sqrt{\sigma_{pz}/\text{mm}}. \quad (11)$$

Thus σ_{py} is limited.

The transverse momentum from the pinching introduces a spread of the total energy of the collision ΔM. If an electron with equilibrium energy has momentum $\vec{p} = -\vec{p}_0 + \vec{\Delta} p$ where $\Delta p = p_0 \theta$ then

$$\frac{\Delta M}{M} \simeq \frac{\theta^2}{8}.$$

Estimating θ as

$$\theta \simeq 2\sigma_{py} n_{osc} / \sigma_{pz}$$

we find that $\Delta M/M \simeq 10^{-3}$ if

$$\frac{\sigma_{py}}{\sigma_{pz}} \sqrt{D_{ey}} < 0.18. \tag{12}$$

Therefore, the transverse momentum caused by the pinching is not a significant source of collision energy spread when Eq. (12) is satisfied.

Beam matching

Due to the instability of positrons at the nodes of the electron distribution, one might question the feasibility of the collisions with $D_e \gg 1$. However, there are at least three reasons to expect that narrow waists in the distribution may be avoided: nonlinearity of the oscillations, dependence of the phase of oscillations on the location of an electron in the electron bunch, and synchrotron radiation.

The effect of the pinching of the electron beam on the stability of positrons can be minimized by the proper choice of the initial conditions for the electron beam entering the interaction region (IR). We use the following approach. Let us specify the ellipse of the electron beam

$$\left(\frac{y}{\sqrt{2\epsilon/k}}\right)^2 + \left(\frac{y' + \alpha y}{\sqrt{2\epsilon k}}\right)^2 = 1 \tag{13}$$

where $\alpha = k'/2k$, and

$$k^2(z) = \frac{D_e}{\sigma_{pz}^2} \sqrt{\frac{2}{\pi}} e^{-2(z/\sigma_{pz})^2} \tag{14}$$

At the IP the two bunches are matched if $\sigma_{ey}^2 = \langle y^2 \rangle = \sigma_{py}^2$ and $\alpha = 0$. For matched beams the emittance and σ'_{py} are defined:

$$\epsilon = k(0)\sigma_{py}^2, \quad \sigma'_{py} = k(0)\sigma_{py} \tag{15}$$

For large D_e, and near the center of the positron bunch, electrons oscillate rapidly. Since emittance is preserved, as long as

$$\left|\frac{d}{dz}\frac{1}{k(z)}\right| \ll 1 \tag{16}$$

the ellipse changes adiabatically.

Eq. (16) is valid for $|z| \leq z_{min}$ where

$$\left|\frac{d}{dz}\frac{1}{k(z)}\right|_{z_{min}} = 1,$$

or

$$k < k_{min} \simeq \frac{2}{\sigma_{pz}}, \quad |z| < z_{min} = \sigma_{pz} \ln\left[\frac{k(0)}{2k_{min}}\right]. \tag{17}$$

The ellipse on the phase plane at $z = z_{min}$ is given by Eq. (13) with $k = k_{min}$. For larger $|z|$ positron density decreases, and oscillations degenerate into free motion:

$$y = y_{min} + (z - z_{min})y'_{min}, \quad y' = y'_{min}$$

That defines the ellipse at the first quad of the IR, i.e. at $z = -L$:

$$\left(\frac{y + ly'}{\sqrt{2\epsilon/k_{min}}}\right)^2 + \left(\frac{y' + \alpha_{min}(y + ly')}{\sqrt{2\epsilon k_{min}}}\right)^2 = 1 \tag{18}$$

where $l = L - z_{min}$.

In the simulations the initial conditions at $z = -L$ have been generated as

$$y = \sigma_\xi(1 + \alpha_{min}l)\xi - \sigma_\eta l\eta$$

$$y' = -\sigma_\xi\alpha_{min}\xi + \sigma_\eta\eta$$

where ξ and η are random numbers with a Gaussian distribution in the interval from -1 to 1, and

$$\sigma_\xi = \sigma_{py}\sqrt{\frac{2k(0)}{k_{min}}}, \quad \sigma_\eta = \sigma_{py}\sqrt{2k(0)k_{min}}, \quad \alpha_{min} = \alpha(k_{min})$$

The 100 trajectories given by Eq. (6) and such initial conditions are shown in Fig. 4. The pinches almost disappeared, and the distribution of electrons within the interaction area

$|z| < \sigma_{pz}$, $|y| < \sigma_{py}$ is practically uniform. The result is robust: the small variations of k_{min} do not change this result significantly. Fig. 5 shows the variation of the transverse rms size σ_{ey} of the electron beam along the IR. It is small for $k_{min}\sigma_{pz} \simeq 2$. The absolute value of $y(-L)$ and $y'(-L)$ are moderate:

$$y(-L) \simeq \sigma_{py}(\frac{L}{\sigma_{pz}})D^{1/4}, \quad y'(-L) \simeq (\frac{\sigma_{py}}{\sigma_{pz}})D^{1/4} \tag{19}$$

Practically, $y(-L)$ is of the order of a millimeter.

Conclusion

A beauty factory based on a SRF linac with impedance as at CEBAF can be designed only with a very large electron disruption parameter. We have presented arguments and results of model simulations which indicate that stability of the SR beam is consistent with high luminosity. If suppression of the kink instability is confirmed, that would be a significant argument in favor of asymmetric collisions. Much more elaborate simulations are needed before a completely sound conclusion may be drawn, but the situation does not look hopeless. Assuming such optimism is justified, a consistent set of parameters has been generated [8] for a B-factory with luminosity $L = 10^{34}/\mathrm{cm}^2\,\mathrm{sec}$. A linac-SR scheme promises very high luminosity and seems to be feasible.

Acknowledgments

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Figure captions

Fig. 1. Pinch of a beam with zero emittance: electron trajectories along the IR.

Fig. 2. Disruption of an electron beam with nonzero emittance. Decoherence is the result of the dependence of the oscillation frequency on amplitude for the transverse Gaussian bunch. The choice of the initial conditions is explained in the text.

Fig. 3. Transverse rms beam size along the IR for the unmatched beam of Fig. 2.

Fig. 4. Trajectories for the matched beam where $D_e = 120.0$. The electron distribution within $|z| < 2\sigma_z$, $|y| < \sigma_{py}$ is rather uniform.

Fig. 5. Variation of the rms σ_{ey} for the matched electron beam along the IR; trajectories are shown in Fig. 4 and $D_e = 120.0$.

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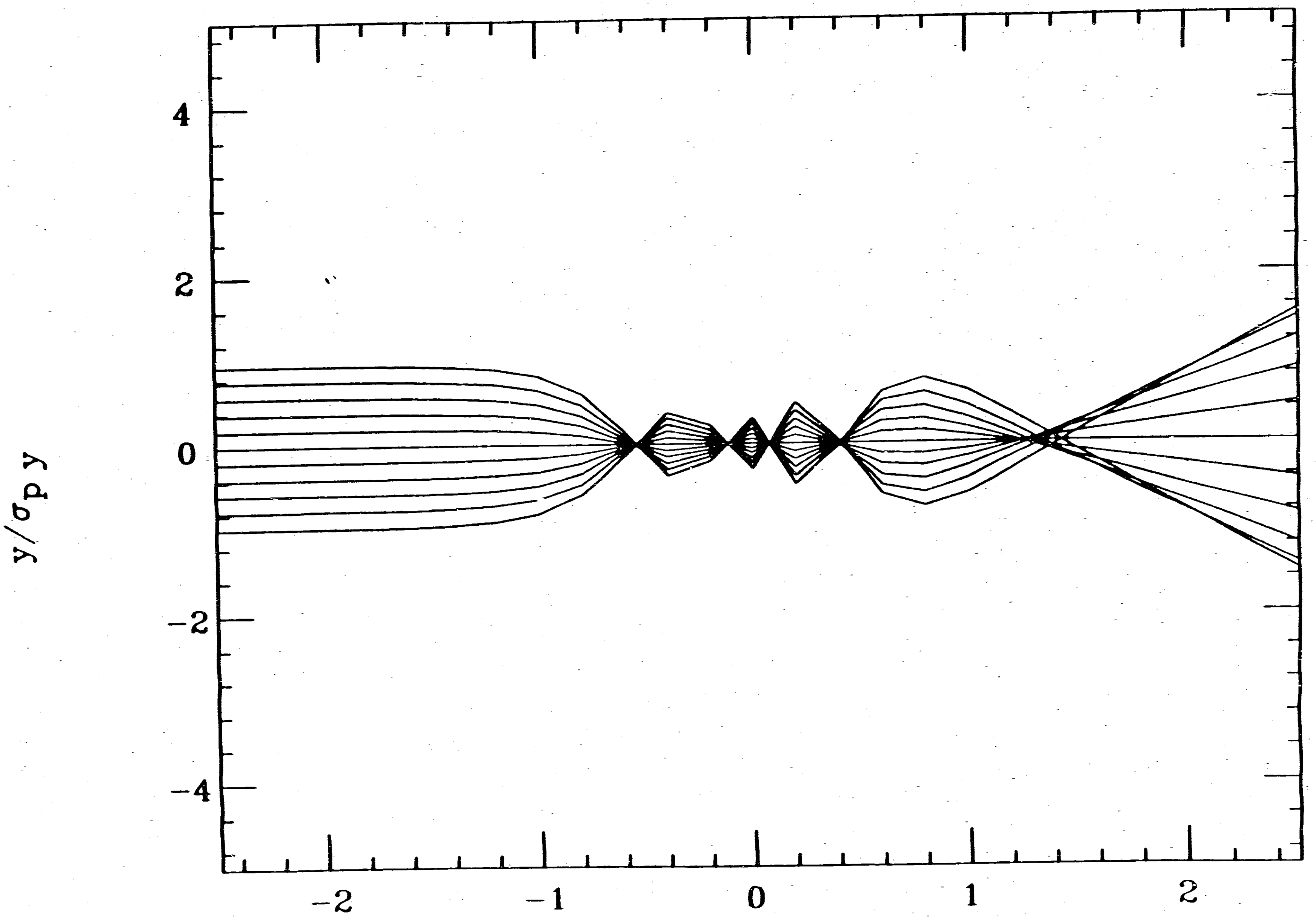

Figure 1. $z/\sigma_{p\,z}$, $D = 120.0$, $\xi p = 0.0$

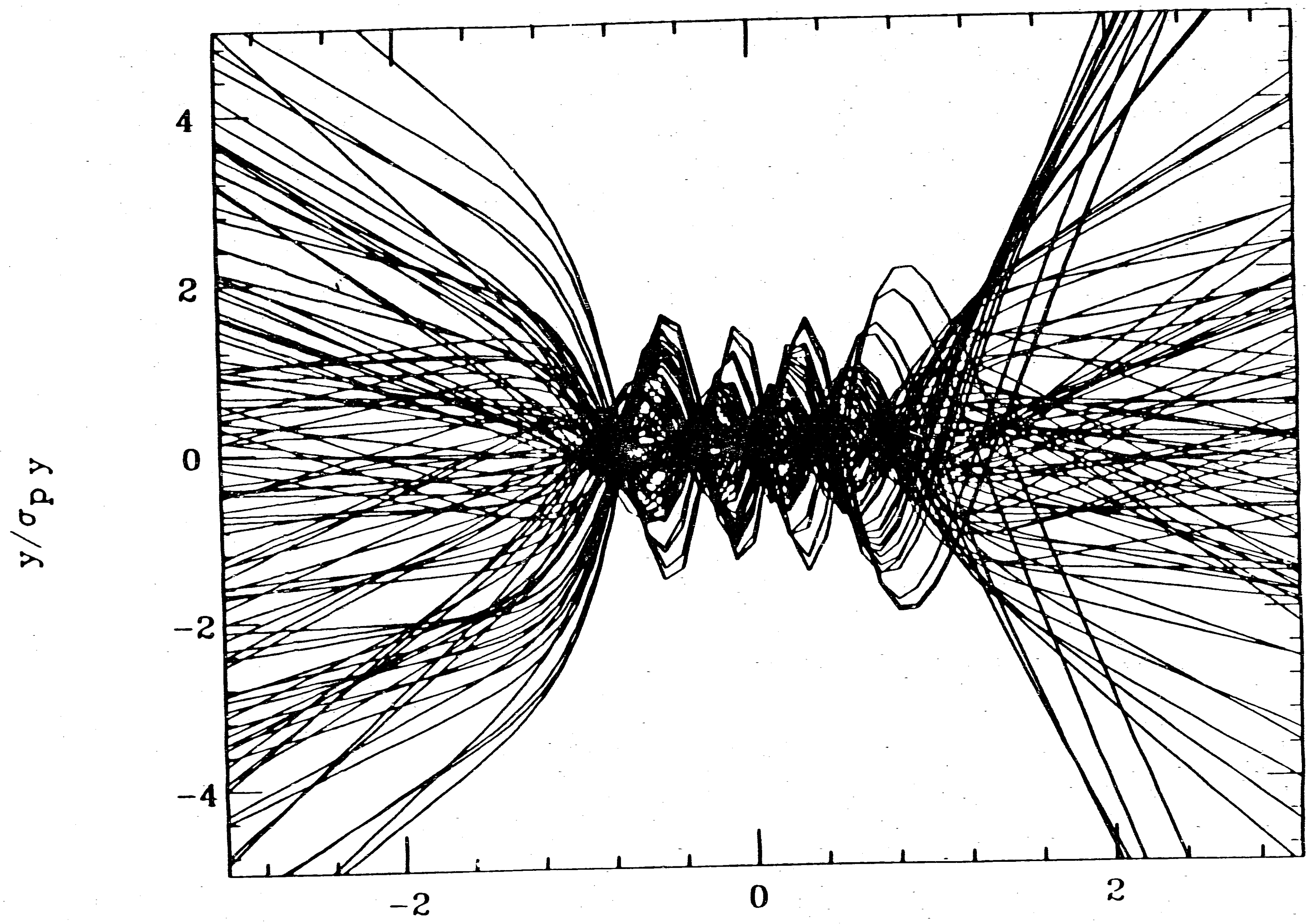

Figure 2. Trajectories of the unmatched beam

z= −3.02 D= 120.0 sy/σ_p= 1.00 σyp= 1.00 alph= 0.00

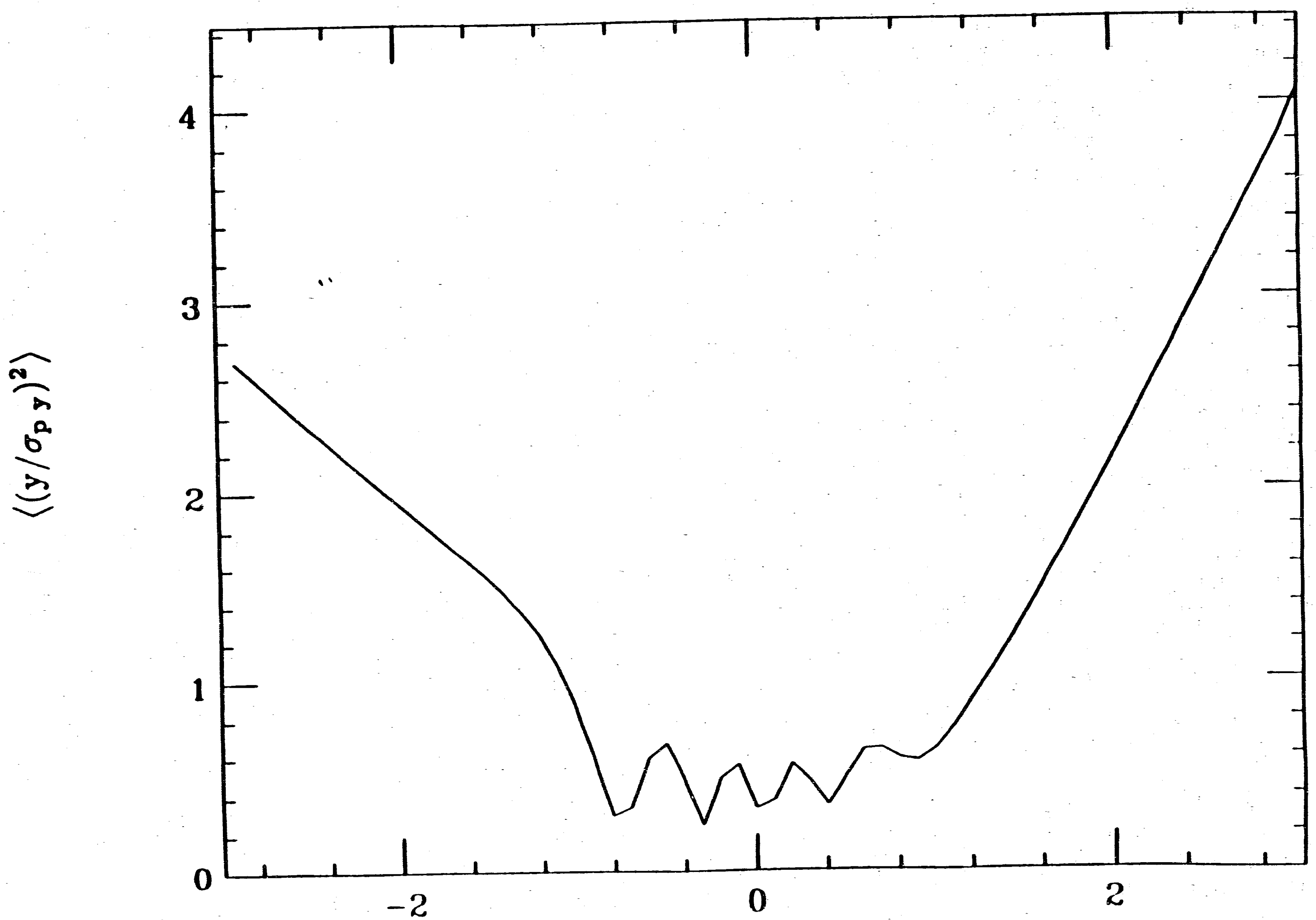

Figure 3. Transverse rms of the electron beam. Unmatched beam

$z = -3.02$ $D = 120.0$ $sy/\sigma_p = 1.00$ $\sigma yp = 1.00$ alph= 0.00

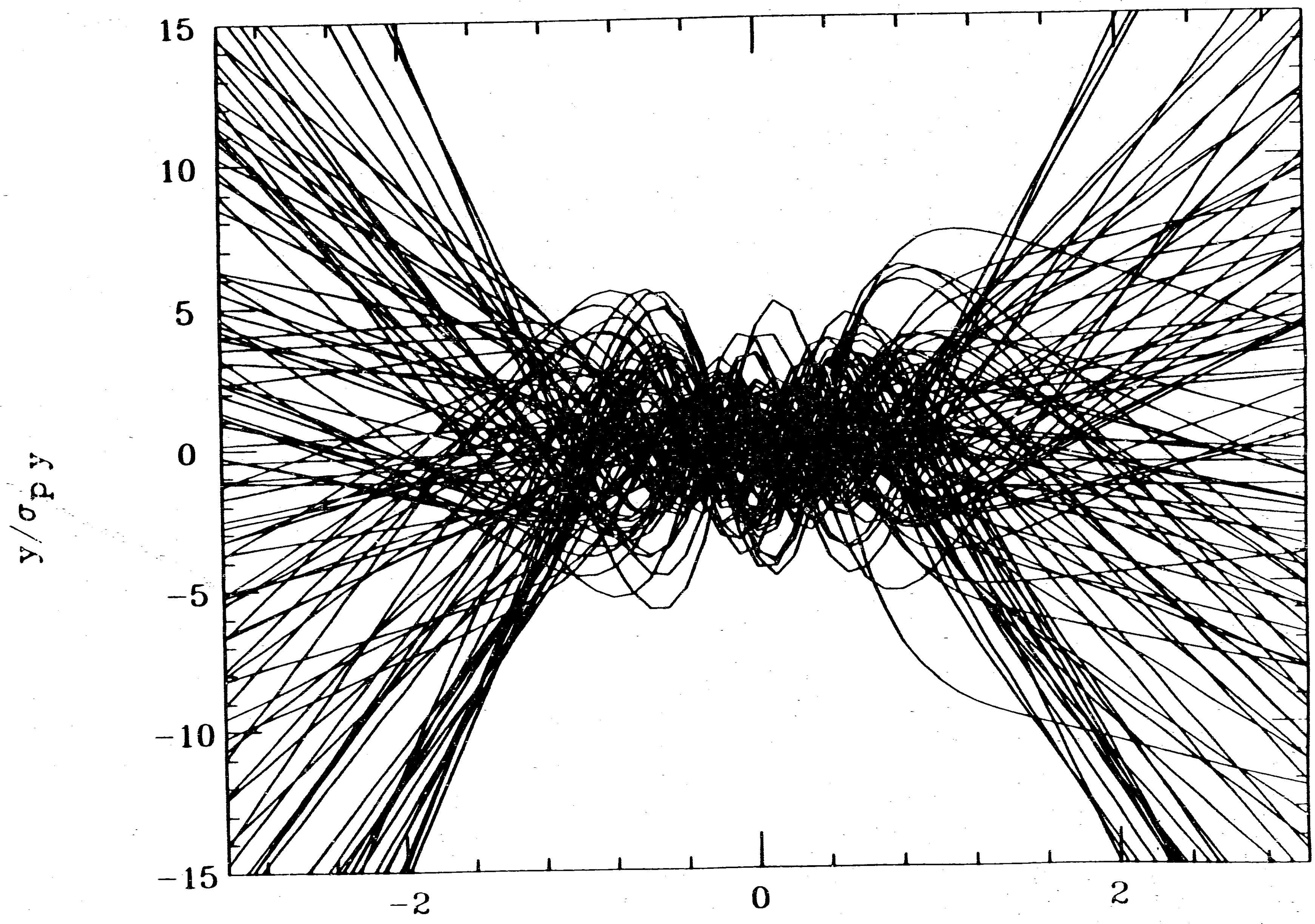

Figure 4. Trajectories of the matched beam

z = −3.02 D= 120.0 sy/σ_p= 3.13 σyp= 6.26 alph = 1.26

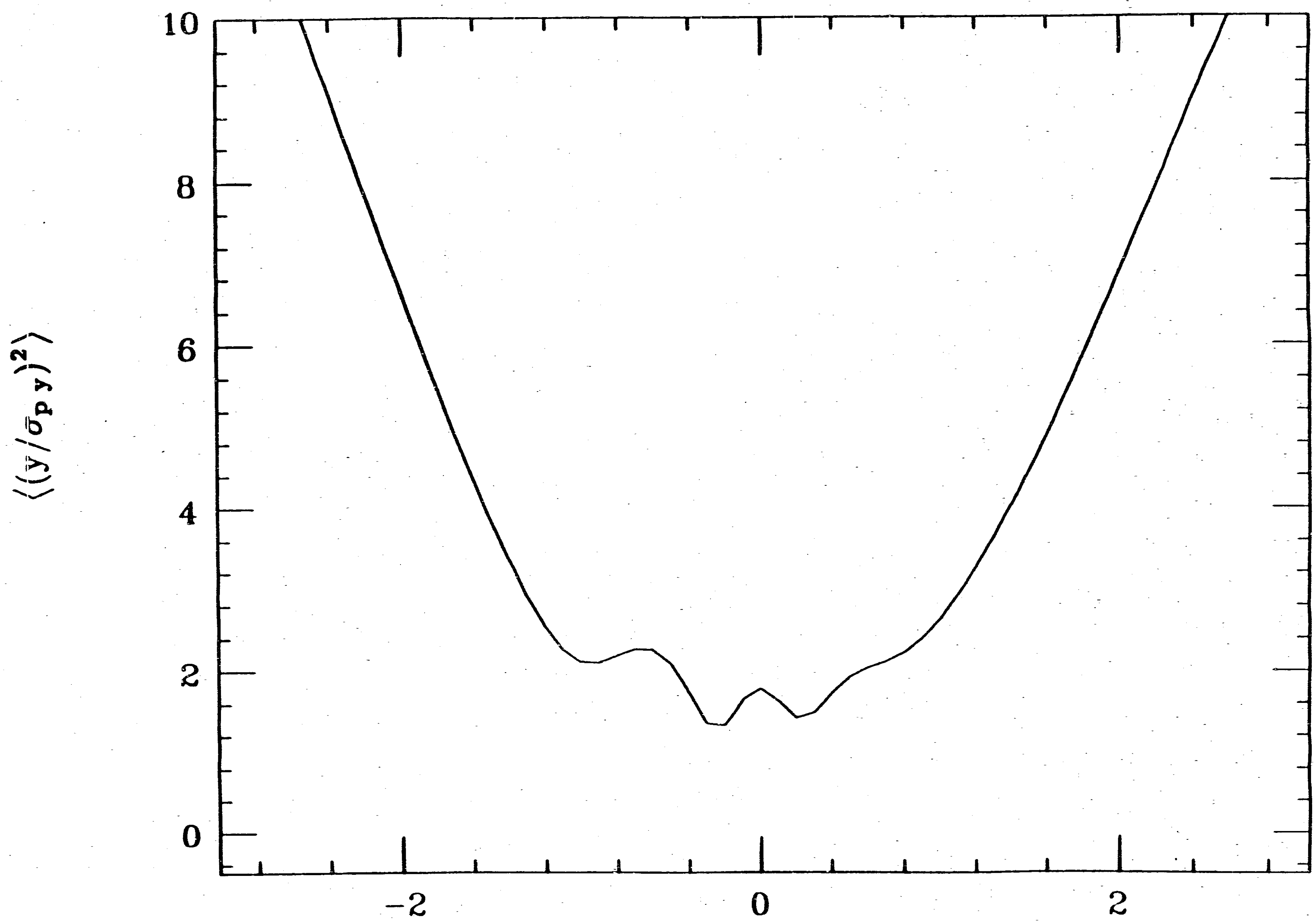

Figure 5. Transverse rms for the matched beam

z= −3.02 D= 120.0 sy/σ_p= 3.13 σyp= 6.26 alph= 1.26

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