COMPUTER SIMULATIONS OF THE BEAM-BEAM INTERACTION

AND MEASUREMENTS WITH PETRA

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Summary

The beam-beam interaction is simulated on a digital computer taking into account all three oscillation modes with quantum fluctuation and damping. It is shown that small asymmetries in phase advance between the interaction points and spurious dispersions at the interaction points are the main causes of an increase of the beam height and a corresponding loss of luminosity. A good agreement between simulations and measurements is found and the operating conditions for PETRA are improved according to the predictions of the simulations.

Introduction

Observations at PETRA have shown that the beam height increases continuously with the currents of the colliding beams[1,2,3]). There is no threshold for this effect; the increase starts at very low currents and can reach a factor of 8 or more often without reducing the life time.

Up to now there is no theory which quantitatively describes the blow-up which therefore is studied by computer simulations. They show the same behaviour of the beam height as observed in PETRA and are used to investigate the dependence on various parameters. The simulations show that machine imperfections are the main causes for an increase of the beam height, especially small differences in betatron phase advance between the interaction points, and spurious dispersions at the interaction points. The asymmetries of betatron phase advance excite a series of resonances which become increasingly important with the number of interaction points[4]). The spurious dispersions lead to a coupling of the synchrotron and betatron oscillations and excite additional resonances[5,6]).

Asymmetries of the phase advance are mainly caused by orbit distortions in sextupoles, and spurious dispersions are produced by orbit distortions in quadrupoles and sextupoles. A good orbit correction is therefore important. The asymmetries and dispersions which can cause an increase of the beam height are, with present means, too small to be measured directly. It is thus very difficult to suppress them.

Computer Simulations

In simulating the beam-beam interaction the change of the oscillation amplitudes of the particles is studied by following the particle motion over a large number of revolutions[4-10]). In the simulations presented here, 64 particles are observed during the following numbers of revolutions (damping times)

E/GeV	7	11.3	17.9
revolutions	100000(8)	45000(15)	14000(20)

The space charge forces are calculated exactly for a relativistic bunch with a gaussian particle distribution. The change of the betatron angles x' and z' at each interaction point is then given by[4])

$$\begin{pmatrix} \Delta x' \\ \Delta z' \end{pmatrix} = -\frac{2\pi}{1-V} \int_0^{1-V^2} \exp\left\{-as - \frac{bs}{1-s}\right\} \begin{pmatrix} x\xi_x/\beta_{xo} \\ \dfrac{z\xi_z/\beta_{zo}}{1-s} \end{pmatrix} \frac{ds}{\sqrt{1-s}} \quad (1)$$

with $V = \sigma_z/\sigma_x$

$$a = \frac{1}{2}\frac{x^2}{\sigma_x^2 - \sigma_z^2} \qquad b = \frac{1}{2}\frac{z^2}{\sigma_x^2 - \sigma_z^2}$$

ξ_x and ξ_z are the horizontal and vertical space charge parameters.
The integrals were calculated for 75x200 points with a spacing of $0.2\,\sigma_x$ and $0.2\,\sigma_z$ between the points. For each passage of a particle, $\Delta x'$ and $\Delta z'$ are interpolated quadratically. The longitudinal motion of the interaction point seen by a particle due to its phase oscillation is always taken into account. The ratio of the longitudinal standard deviation to the vertical amplitude function is 0.1.

Between the interaction points the betatron oscillations and the synchrotron oscillation are transformed linearly. The damping is included in the linear transformation. The quantum fluctuation is simulated by applying random kicks on all three modes of oscillation at each interaction point. Since in a real machine the kicks occur at arbitrary betatron phase distances from the interaction point, in the simulation x and x' and also z and z' are changed by different random kicks. This means that the beam height is assumed to be produced by a spurious vertical dispersion in the magnets.

The following PETRA parameters are used:
$Q_{xo} = 25.2$, $Q_s = .07$, $\sigma_{x\beta}/\sigma_{z\beta} = \beta_{xo}/\beta_{zo} = 15$

with

Q_{xo} = horizontal betatron wave number

Q_s = synchrotron wave number

$\sigma_{x\beta, z\beta}$ = horizontal and vertical standard deviation

$\beta_{xo,zo}$ = horizontal and vertical amplitude function

The increase of beam height is characterized by

$$\frac{1}{\sigma_{z\beta}}\sqrt{<z_\beta^2>} = \frac{1}{\sigma_{z\beta}}\sqrt{\frac{1}{N}\sum_{i=1}^{N} z_{\beta i}^2} \quad (2)$$

N includes all particles at all interaction points and all revolutions after 4 damping times. The same quantity is calculated for

the horizontal coordinates but it is much smaller than the increase of beam height and not considered here.

The applied distortions, i.e. asymmetries of the betatron phase advances and spurious dispersions, have the following values:

$\delta Q_{x,z} = \pm.02$, $D_{xo} = \pm 11$ cm, $D_{zo} = \pm 2$ cm (2 IP)

$\delta Q_{x,z} = \pm.03$, $\pm.01$, $D_{xo} = \pm 11$, ± 4 cm,

$\qquad D_{zo} = \pm 2$, ± 1 cm (4 IP)

$Q_{x,z} = \pm.035$, $\pm.025$, $\pm.015$, $\pm.005$,

$\qquad D_{xo} = \pm 11$, ± 8, ± 5, ± 2 cm,

$\qquad D_{zo} = \pm 2$, ± 1.5, ± 1, $\pm.5$ cm (8 IP)

Asymmetries of $\delta Q_{x,z} = \pm.035$ can be produced by orbit bumps which contain sextupoles. Horizontal dispersions of ± 11 cm and vertical dispersions of ± 2 cm correspond to spurious dispersions which are measured in the straight sections and scaled for the interaction point.

Figs. 1 to 5 show the increase of beam height as a function of the vertical betatron frequency. The resonances are identified by counting the betatron oscillations. The particles usually stay only a short time (order of the damping time) on a resonance. When they have changed their frequencies by changing their amplitudes they often run into another resonance.

Fig. 1: Increase of beam height without distortions for different $\xi_{x,z}$
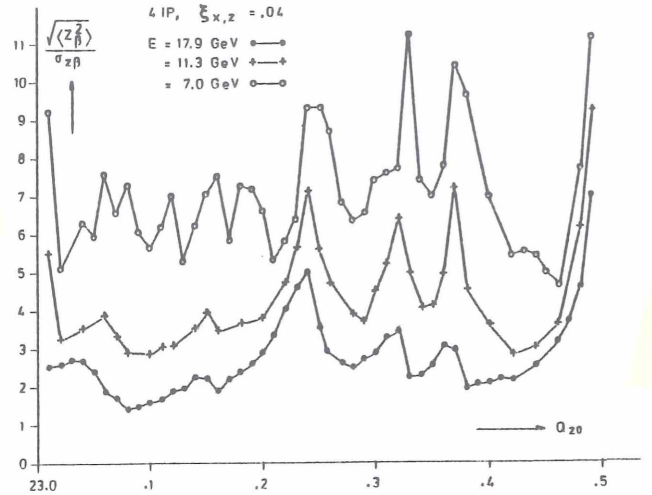

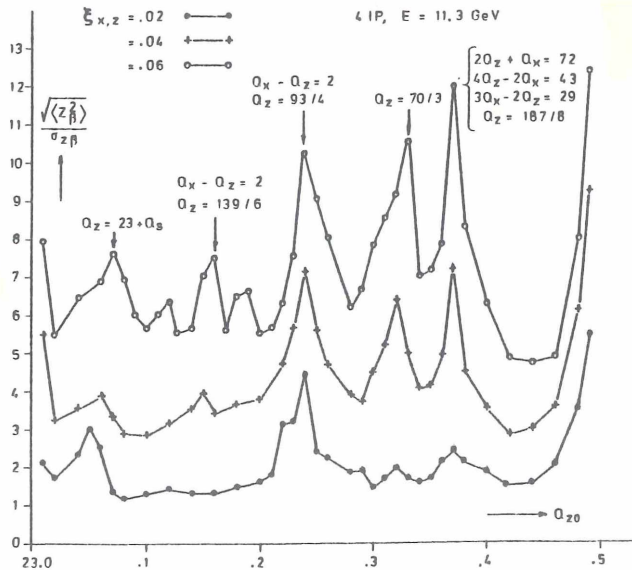Fig. 3: Increase of beam height with distortions for different energies

Fig. 2: Increase of beam height with distortions for different $\xi_{x,z}$
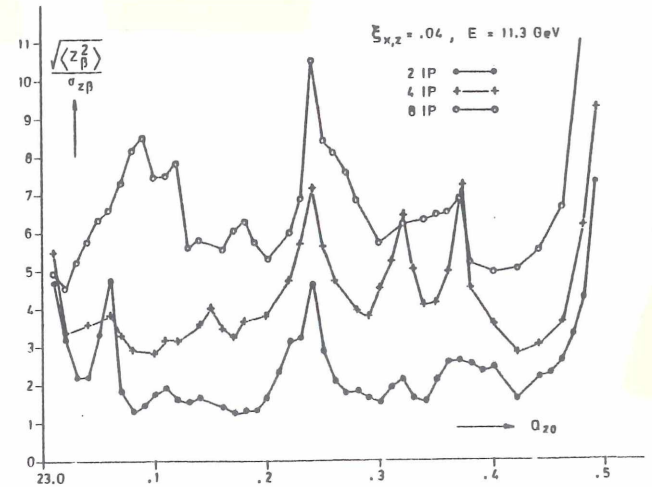

Fig. 4: Increase of beam height with distortions for different numbers of interaction points

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Most of the simulations are done for the case "weak-strong" where the space charge potential is kept constant. These simulations describe also the situation where, due to small differences in beam currents, one beam is blown up and the other not[1]). But also the case "strong-strong" is simulated with two beams having the same height (Fig. 5). This is achieved by changing the space charge potential at intervals of one damping time according to the change of the beam dimensions. Here one has to distinguish between the initial space charge parameter $\xi_{xo,zo}$ and the space charge parameter $\xi_{x,z}$ which is obtained after 15 damping times when the beam height has reached an equilibrium.

4 IP, E = 11.3 GeV

$\xi_{xo,zo} = .04$, $\xi_x = .025 \div .03$, $\xi_z = .005 \div .025$ •——•
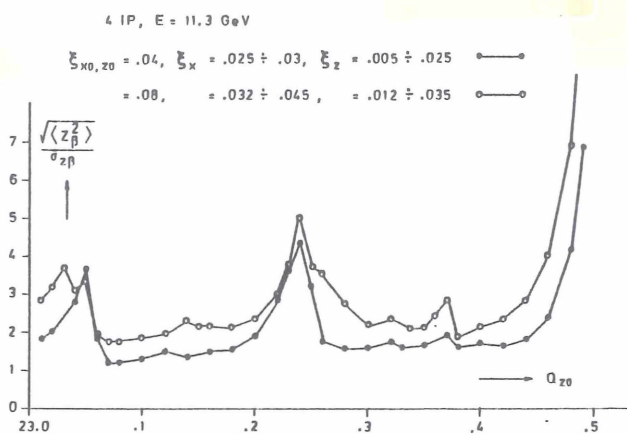
$= .08$, $= .032 \div .045$, $= .012 \div .035$ ○——○

Fig. 5: Increase of beam height with distortions for the case "strong-strong"

Measurements with PETRA

Several experiments with PETRA were done to check the simulations. The luminosity as well as the beam height were measured as a function of several parameters[3]). Thus it was shown that the increase of beam height is about the same with an odd working point ($Q_{xo} = 25.2$, $Q_{zo} = 23.3$) as with an even working point ($Q_{xo} = 26.2$, $Q_{zo} = 24.3$) for the same $\xi_{x,z}$ and 4 interaction points. Interaction in long straight sections ($\beta_{xo} = 50$ m, $\beta_{zo} = 32$ m) gave the same increase of beam height as interaction in short straight sections ($\beta_{xo} = 2.2$ m, $\beta_{zo} = .15$ m). Both agree very well with the simulations. The dependence on the number of interaction points was also, at least quantitatively, found to be in agreement with the simulations.

It is difficult to check the influence of asymmetries and dispersions quantitatively since they are too small to be measured. But their influence can be seen in the measurements. Fig. 6 shows a comparison of luminosity measurements with $Q_{zo} = 25.3$, the usual working point, and with $Q_{zo} = 25.1$. For the latter the simulations
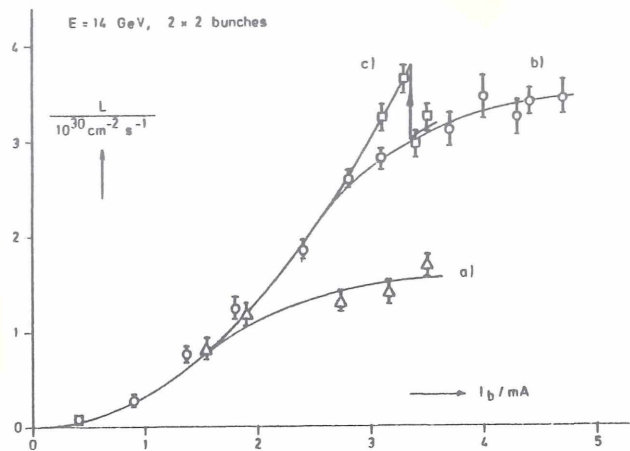
E = 14 GeV, 2 × 2 bunches

Fig. 6: Luminosity as a function of bunch current, a) $Q_z = 23.3$, b) $Q_z = 23.1$, c) $Q_z = 23.1$ with minimization of the horizontal dispersion

tions have shown that the increase of beam height should become appreciably smaller if the asymmetries are reduced and the spurious dispersions at the interaction points are compensated. Curves a) and b) show the luminosity for the two working points after a careful orbit correction and minimizing spurious vertical dispersions around the machine. Curve c) shows measurements for $Q_{zo} = 25.1$ with a jump which was caused by minimizing the horizontal dispersion at the interaction points using orbit bumps. The criterion for the minimization was the blow-up, and the required change of the dispersion was so small that its contribution to the beam width was smaller than 3%. The space charge parameters at the maximum luminosity are $\xi_x = .025$ and $\xi_z = .038$.

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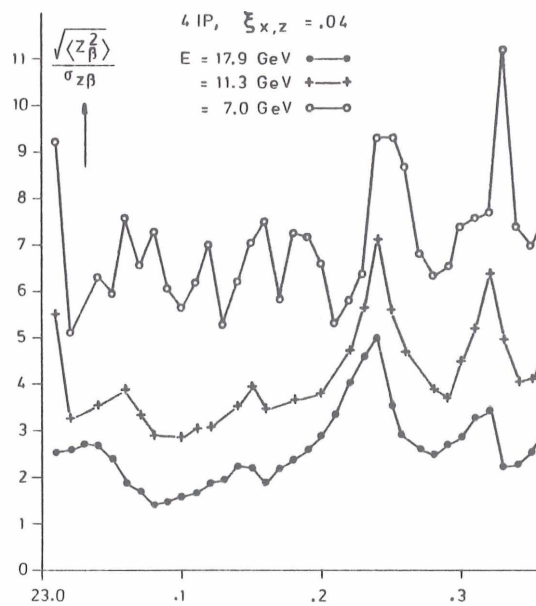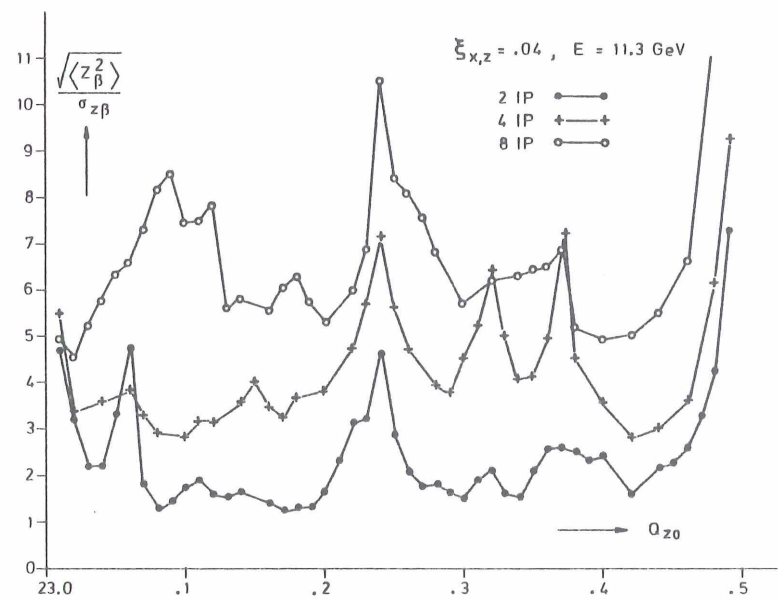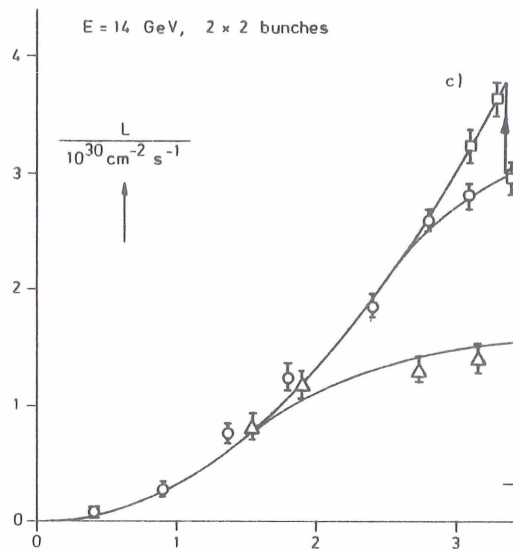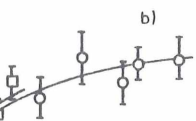
Fig.

Q_{zo}

.4

.5

3

Fig. 4

Fig. 6

b)

a)

I_b / mA

4   5