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DEPENDENCE OF THE LUMINOSITY ON VARIOUS MACHINE PARAMETERS AND THEIR OPTIMIZATION AT PETRA

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Summary

The luminosity of a storage ring is determined by the beam currents, by the natural beam size at the interaction points and by the increase in beam height due to the beam-beam interaction. The limitation of the currents, the variation of the beam size and the minimization of the blow-up as predicted by computer simulations are discussed. Results of the optimization of the luminosity in PETRA are shown.

Introduction

The luminosity L of a storage ring determines the counting rate of a process if multiplied with the cross section of the process. The luminosity follows directly from the beam currents or number of particles and from the geometry of the intersection. For head-on collision it is

$$(1) \quad L = \frac{f_o \; B \; N_b^2}{4\pi \; \sigma_x \sigma_z}$$

with f_o = revolution frequency, B = number of bunches per beam, N_b = number of particles per bunch, $\sigma_{x,z}$ = standard deviation of the horizontal and vertical particle distribution, respectively.

The maximum luminosity is determined by three types of limitations: 1. Limitations of the beam currents, 2. limitations of the cross section, and 3. the blow-up of the beams due to the electromagnetic field of the colliding bunches.

The currents can be limited by single beam instabilities, by the available rf power and by the blow-up due to the beam-beam interaction. In the storage ring PETRA all three effects play a role. The currents are limited at low energies (below 11 GeV) by the beam-beam interaction, at medium energies by satellite resonances and at the highest energies (18 to 20 GeV in 1982) by the rf power.

The beam dimensions at the interaction point are determined by the emittances $\epsilon_{x,z}$, which give the mean dimensions in the whole ring, and by the amplitude functions $\beta^*_{x,z}$, which give the local variation due to the focusing:

$$(2) \quad \sigma_{x,z} = \sqrt{\epsilon_{x,z} \cdot \beta^*_{x,z}}$$

A lower limit for the amplitude function or beta is given by the chromaticity of the quadrupoles nearest to the interaction point. At given chromaticity the beta at the interaction point can be reduced by reducing the free space for the experiments between the quadrupoles. Another limit is given by the bunch length which must be, roughly speaking, smaller than the minimum beta in order to avoid that some particles pass the opposing bunch outside the minimum where the beta is already large. In PETRA the reduction of the free space by a factor of 1.7 and the reduction of both betas at the interaction point by about a factor of 2, the so called mini beta, was a large step to higher luminosities.

The horizontal emittance ϵ_x can be varied in two ways. It is determined by the optics in the arcs, where the synchrotron radiation occurs, and it is determined by the damping. Thus it can be varied by changing the optics or by changing the damping partition between horizontal betatron oscillation and synchrotron oscillation, which is done by changing the revolution frequency, i.e. by changing the orbit in the quadrupoles.

The vertical emittance is either given by the beam-beam interaction or by orbit distortions in quadrupoles and sextupoles. In the latter case it can be minimized by careful orbit corrections.

The beam-beam interaction in PETRA leads, first of all, to an increase of beam height and to a loss of luminosity. The increase can be by a factor of 3 or 5 before the beam life time is decreased. The blow-up is not changed by the mini beta insertion if the ratio of the horizontal to the vertical beta remains constant and if no other parameters are changed. This can easily be seen for the linear part of the space charge forces which determines the space charge parameter ξ, i.e. linear tune shift:

$$(3) \quad \xi_{x,z} = \frac{r_e N_b \, \beta^*_{x,z}}{2\pi\gamma \, \sigma_{x,z}(\sigma_x+\sigma_z)}$$

with r_e = electron radius, γ = relative particle energy.

Computer simulations have revealed some important properties of the mechanism of the blow-up and the main parameters which play a role in this effect. Thus it was found that small machine imperfections are a main cause for a large blow-up. Also the working point plays an important role, and better working points were found as predicted by the simulations.

It should be mentioned that if the storage ring is operated at its optimum the luminosity is always limited by two effects at the same time. If, for instance, the currents are limited by the beam-beam interaction, the beam width can be enlarged so that the maximum currents and the luminosity become larger. The second limit is then given either by single beam instabilities or by the maximum beam width, i.e. by the aperture of the machine. If the currents are limited by single beam instabilities or the available rf power, the beam width can be reduced so that the second limit is given by the beam-beam interaction or by the smallest emittance which can be made.

Current limitations

The maximum bunch currents in PETRA which were ramped from 7 GeV, the injection energy. to higher energies and used for luminosity runs were 4x6.5 mA. They were limited by synchro-betatron resonances which, especially during energy ramping, reduce the life time of the beams. The maximum currents injected into four bunches (two in each beam but without collision) were 4x9 mA, and the maximum current in a single bunch was 20 mA, which was also limited by synchro-betatron resonances so that at the maximum the injection compensated the losses.

There are two mechanisms which excite the above mentioned satellite or synchro-betatron resonances: Spurious dispersions in the cavities[2], which are produced by orbit distortions, and transverse fields with a longitudinal gradient[3,4], which are mainly produced by traversing the cavities off-axis. These resonances can be suppressed in a wide range by orbit corrections[5], however, the orbit is very sensitive to distortions, and the corrections cannot be maintained during the energy ramping. Satellite resonances are avoided as far as possible by staying with the synchrotron and betatron frequencies between the resonances. During the energy ramping this is done by an automatic control system which measures and corrects the frequencies.

A vertical instability[6] which can also limit the bunch current is avoided by bunch lengthening which is achieved by changing the damping partition via the accelerating frequency, i.e. the revolution frequency.

Below 11 GeV per beam the currents are limited by the beam-beam interaction so that, for instance, at 7 GeV the maximum currents are 4x3 mA. Above 18 GeV the currents are limited by the available rf power (in 1982). At 20 GeV the maximum currents were 4x1 mA.

Sometimes the currents are limited by a too large background for the experiments. It can even occur at currents well below the limit if the beams are somewhat blown up by the beam-beam interaction. The background conditions can then very often be improved by orbit corrections in the experimental regions. A better shielding of the experiments also improved the situation.

If the number of bunches is increased from 4 to 8 the maximum total current remains roughly the same in the rf-limited and in the satellite-limited energy region. In the lower energy region where the currents are limited by the beam-beam interaction the blow-up is roughly the same for the same total current. This holds for the usual working points but can be somewhat better for other tunes. For constant bunch currents the blow-up increases strongly with the number of interaction points. Thus increasing the number of bunches does not increase the luminosity per experiment[7].

Mini beta insertion

The amplitude functions or betas in the interaction region are given by

$$(4) \qquad \beta_{x,z}(s) = \beta^*_{x,z} + \frac{s^2}{\beta^*_{x,z}}$$

where s is the distance from the symmetry point. The betas must not become too large in the quadrupoles nearest to the interaction point where they produce a large chromaticity, i.e. strong energy dependence of the betatron frequencies which must be compensated by sextupoles.

Initially the four interaction regions in PETRA had a free space of 2x7,5 m each. It was used by the detectors and, in three interaction regions, by compensating solenoids which compensated the solenoid fields of the detectors. After it was shown that PETRA could be operated without solenoid compensation the free space was reduced to 2x4.5 m. The three detectors with solenoids are now running without compensation. Their field polarity is chosen such that they partly compensate each other. The operation of the machine is not affected at higher energies, but at lower energies the performance is somewhat reduced due to the larger coupling of the horizontal and vertical betatron oscillations.

The horizontal and the vertical beta at the interaction point were reduced from 250 to 120 cm and from 15 to 8 cm, respectively[8,9,10]. The calculation gives an enlargement of the luminosity by a factor of 2. The first measurements gave nearly a factor of 3. The reason for the additional increase was a new alignment of all quadrupoles which was done together with the reduction of the free space. Thus machine imperfections were removed and the blow-up of the beams was reduced as will be discussed later. The additional increase was lost after several months when the quadrupoles were again somewhat displaced.

The mini beta is now limited by the chromaticity. A further reduction of the betas reduces the energy acceptance. This holds for a compensation of the chromaticity with two families as well as with four families of sextupoles, although the situation is somewhat better with four families.

A new scheme, the so called micro beta, is now under discussion[11], where superconducting quadrupoles are incorporated in the detectors at a distance of only 0.9 m from the interaction point. A vertical beta of about 2 cm seems possible at 23 GeV with a reasonable energy acceptance.

Variation of the emittance

The horizontal emittance is given by quantum fluctuation and damping. The emission of a photon changes the amplitude of the betatron oscillation proportionally to the dispersion at that position. Thus changing the dispersion in the bending magnets by changing the focusing in the arcs yields a variation of the horizontal emittance. This must be done without changing the tune of the machine and without producing a dispersion in the straight sections which would excite satellite resonances and increase the blow-up. Under these conditions a variation of the horizontal emittance by a factor of 2 to 3 is obtained in PETRA.

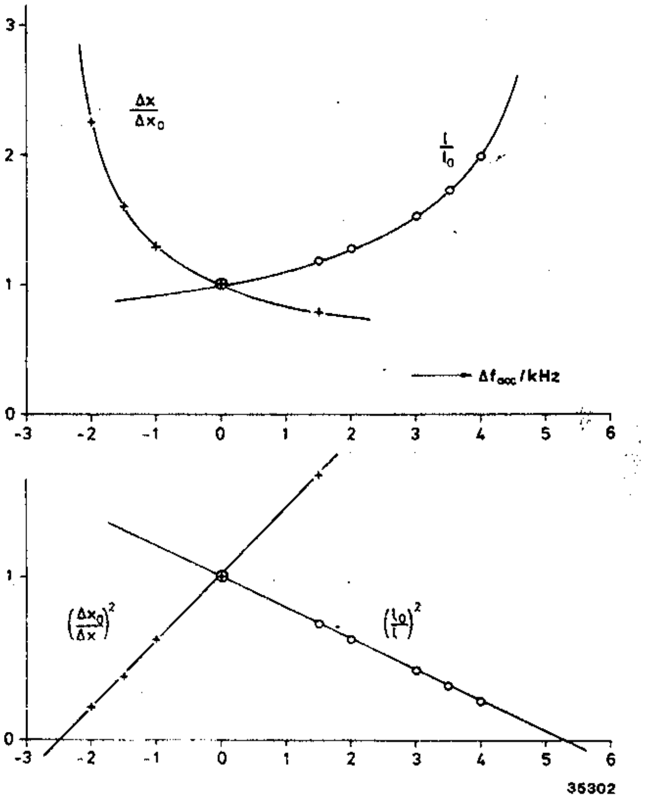

Fig. 3: Normalized beam width Δx (measured with scrapers) and bunch length l (measured with a fast diode) as a function of the accelerating frequency.

If the equilibrium orbit of the machine passes off-axis through a quadrupole in which the dispersion does not vanish, the radiation losses in the quadrupole are different for particles with positive or negative energy deviation. This adds some damping or antidamping to the synchrotron oscillation. If the equilibrium orbit is displaced in the same direction as the orbit of particles with positive energy deviation the synchrotron oscillation is damped since a positive energy deviation gives larger radiation losses. Therefore, a reduction of the accelerating frequency, i.e. a lengthening of the equilibrium orbit, increases the synchrotron damping, and an enlargement of the accelerating frequency decreases the synchrotron damping. Since the sum of the damping constants of the synchrotron and betatron oscillations cannot be changed[12] the betatron damping is changed with the opposite sign as the synchrotron damping.

Fig. 1 shows the beam width and the bunch length (or energy spread) which are proportional to one over the square root of the damping. The presentation in (b) shows the change of the damping. The distance of the synchrotron pole from the central frequency (499 664 kHz) is twice the distance of the betatron pole since the synchrotron damping is twice the betatron damping in a machine without synchrotron magnets. Maximum changes of beam width and bunch length by a factor of 2 to 3 are obtained. A change of the damping partition has the advantage that it can be done during a luminosity run so that the operating conditions can always be optimized[13].

Computer simulations of the beam-beam interaction

In simulating the beam-beam interaction on a digital computer, significant progress was made in 1980 [14,15,16,17]. Since that time, many simulations were done by several authors, and a better understanding of the mechanism of the blow-up was achieved. In the following the simulations for PETRA are briefly described.

The exact space charge forces of an opposing bunch with a Gaussian particle distribution were calculated for a two-dimensional grid of points and then interpolated quadratically for calculating the transverse kick of a particle at each passage. The longitudinal motion of the interaction point seen by a particle due to its synchrotron oscillation is always taken into account. Between the interaction points the horizontal and vertical betatron oscillation and the synchrotron oscillation are transformed linearly. The radiation damping is included. The quantum fluctuation is simulated by applying random kicks on all three modes of oscillation. The motion of particles is observed over several damping times, i.e. over a large number of revolutions. Both cases, "weak-strong" and "strong-strong" were investigated.

As an example Fig. 2 shows the vertical motion of a single particle in a phase diagram. The horizontal axis gives the position and the vertical axis the angle of the vertical betatron oscillation at a symmetry point of the machine for each revolution. The vertical amplitude of the particle starting with zero amplitudes remains within one or two standard deviations of the Gaussian distribution of the opposing bunch during the first 8000 revolutions. Then its amplitude increases rapidly due to quantum fluctuation and the nonlinearity of the space charge forces, and it moves into a third order resonance where the phase advance is about 2π/3 + 2πx integer (a). After about three quarters of a damping time it comes out of resonance and leaves the three fixed points, but is immediately captured by other three fixed points of the third order resonance (b) which are a mirror image and equivalent to the first three points (without optical asymmetries). After about 600 revolutions the particle leaves the third order resonance and its amplitude decreases.

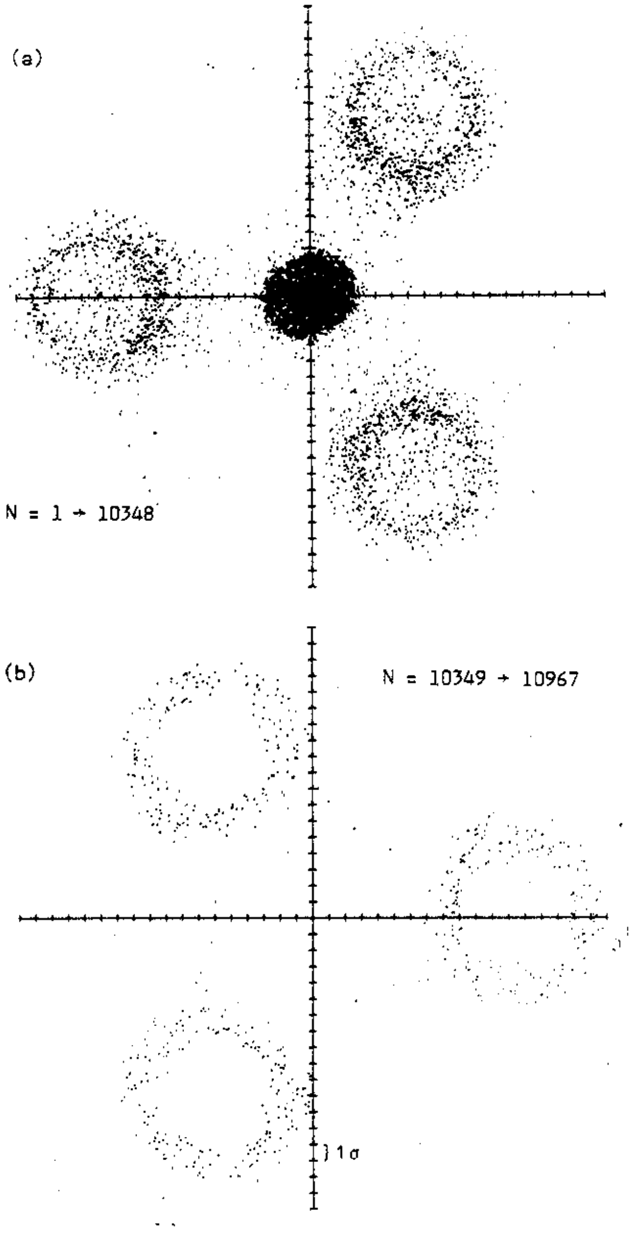

Fig. 2: Phase diagram z-z' ($Q_x = 25.2$, $Q_z = 23.32$, 1 damping time = 3000 revolutions)

A similar behaviour can be observed for several resonances. More often, however, coupling resonances between horizontal and vertical betatron oscillations appear. These resonances can be found by counting the betatron oscillations and by observing the variation of the amplitudes. In all cases the particles usually do not stay longer than a damping time on a resonance. Due to quantum fluctuation and damping they can leave the resonance and can then be captured by another resonance.

The computer simulations have shown that small disturbances of the ideal machine increase the number and strength of the resonances which can be excited. Those disturbances are small differences in betatron phase advance between the interaction points and spurious dispersions at the interaction points. Thus machine imperfections enlarge the blow-up of the beams and become more important with increasing number of interaction points.

The increase in beam height is given by the root mean square of the vertical betatron coordinates of many particles over many revolutions:

$$(5) \qquad \sqrt{\langle z_b^2 \rangle} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} z_{\beta i}^2}$$

N includes all particles at all interaction points and all revolutions after 4 damping times.

The following PETRA parameters were used in all simulations shown here:

synchrotron wave number	$Q_s = 0.07$
ratio of beam width to height at the interaction point	$\sigma_{x\beta}/\sigma_{z\beta} = 15$
ratio of horizontal to vertical amplitude function at the interaction point	$\beta^*_x/\beta^*_z = 15$
space charge parameter	$\xi_x = \xi_z = 0.04$
number of interaction points	4

Fig. 3 shows the influence of machine imperfections on the blow-up. To reduce the computer time these simulations were done only for the case "weak-strong", however, simulations of the case "strong-strong" have shown[18] that the dependence on the working point is very similar in both cases. The assumed phase asymmetries can be produced by the usually observed orbit displacements in the sextupoles, and the magnitude of the spurious dispersions is scaled from measurements of the dispersions in the straight sections outside the mini beta insertion.

In Fig. 3 three working points are shown. "A" was the first working point for PETRA during the first two years. "B" and "C" were chosen because the computer simulations predicted a smaller blow-up. In "B" the machine was operated in 1981 at 7 and 11 GeV. The blow-up was indeed smaller than in "A". The working point "C" was used above 17 GeV where the beam height is very small since the blow-up goes down with increasing energy. The blow-up in "C" was also smaller than in "A", and the beam height was not so sensitive to vertical orbit distortion as in "B", since the distance from the integer is larger.

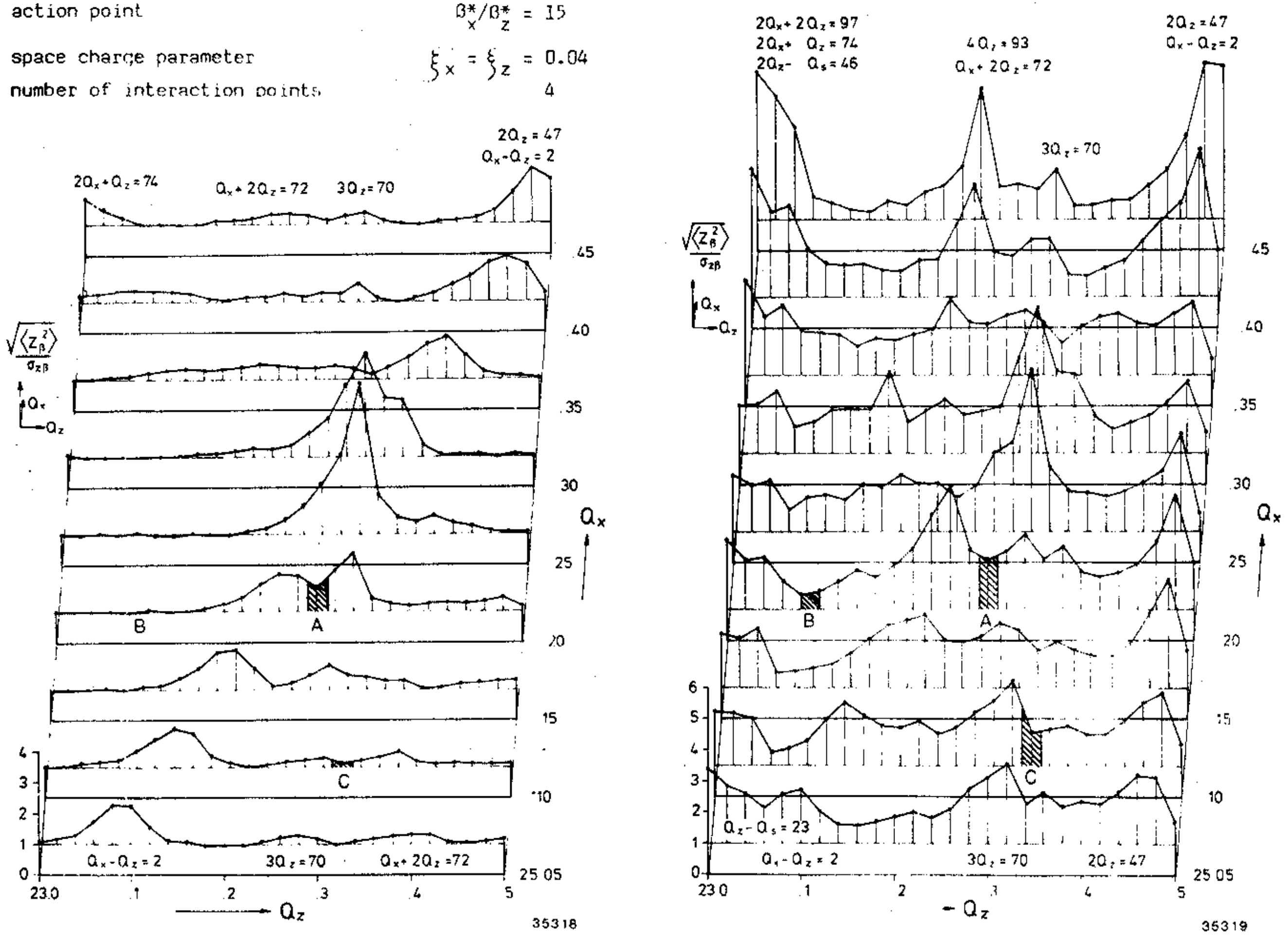

Fig. 3: Increase of beam height as a function at the vertical and horizontal betatron frequency

a) without machine imperfections

b) with machine imperfections ($\delta Q_{x,z} = \pm.03, \pm.01$, $D^*_x = \pm 8.5, \pm 2.8$ cm, $D^*_z = \pm 1.3, \pm .4$)

Luminosities in PETRA

Since March 1981, when the mini beta operation in PETRA was started, many data were taken at 17, 11 and 7 GeV per beam. At the end of 1982 data were also taken between 19 and 20 GeV. Fig. 4 shows the maximum luminosities at these energies. At 19 GeV the maximum luminosity was sharply limited by the available rf power and by the smallest beam size. At 17 GeV the beams were blown up by 10 to 15 % due to the beam-beam interaction, and the currents were close to the limit given by satellite resonances during energy ramping. At 11 GeV the luminosity was limited by the beam-beam interaction and the beams were blown up by 40 %. The currents were also limited by satellite resonances during ramping and the beam width was artificially increased up to an optimum. At 7 GeV the luminosity was sharply limited by the beam-beam interaction and the beam width was reduced during the run by changing the accelerating frequency so that the currents were always at the beam-beam limit. The emittances at the four energies do not scale with E^2 (the natural energy dependence) but with $E^{0.7}$ due to the artificial enlargement given by a change of the optics and the damping partition (s. Table 1).

Energy/GeV	7	11	17	19
optics	MI8E	MI9E	MI9	MG8
hor. emittance/10^{-7}radm	.61	.92	2.0	2.1
change of rf freq./kHz	-1.2	-1	0	0
hor. emittance at changed rf frequency/ 10^{-7}radm	1.13	1.5	-	-
ratio of vert. and horiz. emittance at max. luminosity/%	38	14	1.3	0.7
Q_x	25.20	25.19	25.19	25.10
Q_z	23.13	23.12	23.29	23.35
Q_s	.042	.054	.070	.07
max. luminosity/ $10^{30}cm^{-2}sec^{-1}$	1.9	8	17	4.7
bunch current at maximum luminosity/mA	3	5.7	5.2	2.4
maximum ξ_x	.036	.034	.016	.007
maximum ξ_z	.014	.024	.040	.019
maximum number of inverse nanobarn per day and per experiment	120	360	870	140

Table 1

To suppress machine imperfections as far as possible the orbit must be corrected very carefully. Large luminosities were obtained only with rms-values of the orbit deviations of .5 to 1 mm. Spurious dispersions at the interaction points were compensated with special orbit bumps. Differences in the vertical amplitude functions at the eight quadrupoles nearest to the four interaction points were found in the order of 20 %. Compensating the differences with additional single power supplies[19] on the eight quadrupoles increased the average luminosity by about 15 %. Furthermore, the blow-up assumes a minimum if the currents of the colliding bunches are equal, i.e. the differences in bunch currents should not exceed a few percent[20,21].

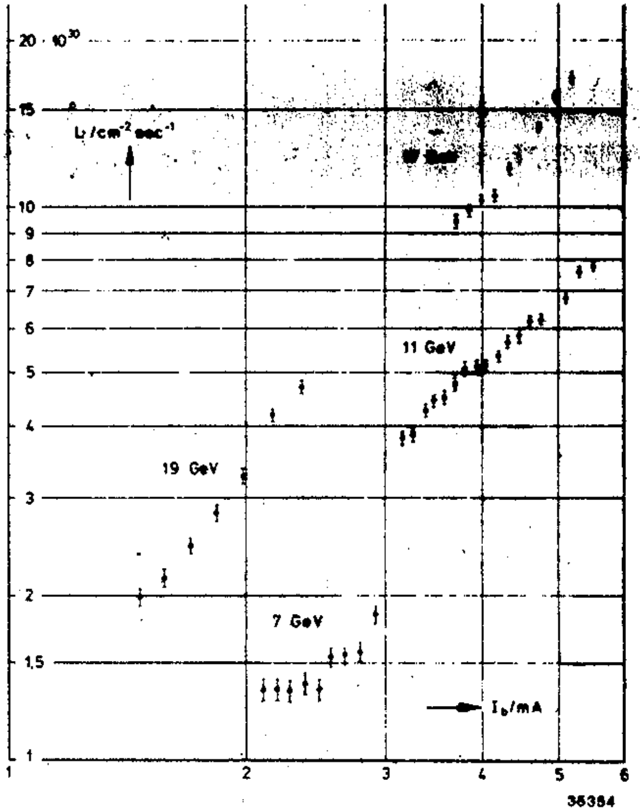

Fig. 4: Luminosity as a function of bunch current. For 19 and 7 GeV the values are averaged over 30 minutes, for 17 and 11 GeV over 15 minutes.

References

1. D. Degèle et al., 11th Intern.Conf.on High Energy Accelerators, Geneva, 16 (1980)
2. A. Piwinski, A. Wrulich, DESY 76/07 (1976)
3. N.A. Vinokurov et al., 10th Intern.Conf. on High Energy Accelerators, Protvino, 254 (1977)
4. R.M. Sundelin, IEEE Trans.V.NS-26,No.3,3604(1979)
5. A. Piwinski, 11th Intern.Conf. on High Energy Accel., Geneva, 638 (1980)
6. R.D. Kohaupt, ibid. 562 (1980)
7. D. Degèle, A. Piwinski, DESY M-82-16 (1982)
8. K. Steffen DESY M-79/23 (1979)
9. J. Roßbach, DESY M-81/01 (1981)
10. PETRA Storage Ring Group,IEEE Trans.V.NS-28,No.3, 2025 (1981)
11. Micro Beta-Studiengruppe, DESY M-82-11 (1982)
12. K.W. Robinson, Phys.Rev.111, 373 (1958)
13. G.A. Voss et al., IEEE Trans.V.NS-26,No.3,2970(79)
14. J. Tennyson, Univ. of Calif., Berkeley (1980) (unpublished)
15. S. Peggs, R. Talman, 11th Intern.Conf. on High Energy Accel., Geneva, 754 (1980)
16. A. Piwinski, ibid. 751 (1980)
17. A. Piwinski, DESY 80/131 (1980)
18. A. Piwinski, IEEE Trans.V.NS-28,No.3,2440 (1981)
19. A. Wrulich, DESY M-82-19 (1982)
20. G.A. Voss, DESY M/VM-79/6 (1979)
21. G.A. Voss, 11th Intern.Conf. on High Energy Accel. Geneva, 748 (1980)