DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

D O R I S at 5 GeV

The DORIS Storage Ring Group

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D O R I S   at   5   GeV

The DORIS Storage Ring Group [†]

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1. Introduction

Recently a broad structure in the invariant mass distribution of muon pairs produced in proton interactions has been observed[1]. One possibility was to interpret this structure as a new quark-antiquark bound state, called Y-particle, and its excited state. The best way to test the correctness of this interpretation and to study the properties of this structure was to produce it in e^+e^- annihilation. Immediately after the discovery of the new structure the DORIS group started preparations to increase the particle center of mass energy of the storage ring DORIS up to the Y-region. Plans for this had existed since 1973.

The electron-positron storage ring DORIS was originally designed to produce sufficiently high luminosities in the energy region between 1 and 3,5 GeV for each beam (center of mass energy between 2 and 7 GeV). In the low energy region luminosity is limited by the beam-beam effect and the luminosity increases with the number of colliding bunches. Expressed naively, the luminosity is then n times the luminosity of a machine with only one electron and one positron bunch, where n is the number of bunches (at DORIS n = 480) in each ring. As a consequence separate storage rings were needed for the electron and the positron beam. It was decided to build two rings one on top of the other. The beams collide at a crossing angle of 24 mrad (fig.1). This crossing angle reduces the luminosity so that the net increase in luminosity is less than the above mentioned factor n. The original DORIS concept and the results achieved with DORIS are described in several papers[2]...[6].

In order to achieve sufficient luminosity at about 5 GeV (single beam energy) with the given rf-power, the multibunch concept had to be abandoned and DORIS had to be changed to a machine with one electron and one positron bunch[7],[8] in which one bunch collides head-on with the other one. In addition two further conditions had to be fulfilled: since synchrotron radiation increases rapidly with the energy of the beam, the counters of the experiments had to be protected against synchrotron radiation. Secondly, the two existing detectors DASP and PLUTO had to be left in their position.

These conditions can only be fulfilled by a machine concept such as the one sketched in fig. 2. With this machine the beams collide head-on although vertical bending is still maintained. Due to this vertical bending the interaction points in the detectors remained unchanged and it was not necessary to move the detectors. The interaction region is protected against synchrotron radiation generated in the curved sections by the vertical bending. A re-installation of the double rings is possible within a relatively short time.
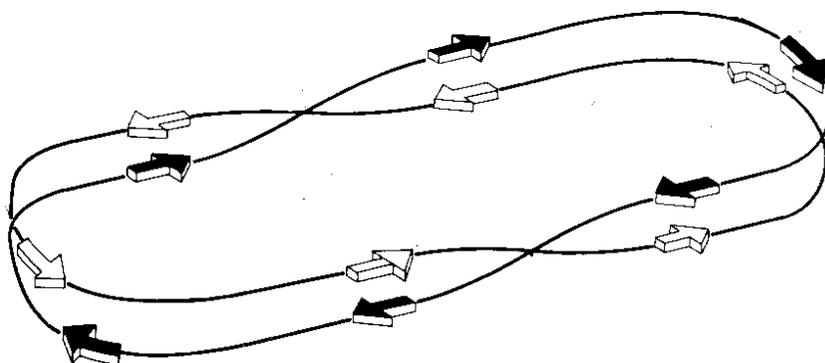
Fig.1 The original DORIS double ring concept. Each ring is filled
with 480 bunches. The collision takes places with the help
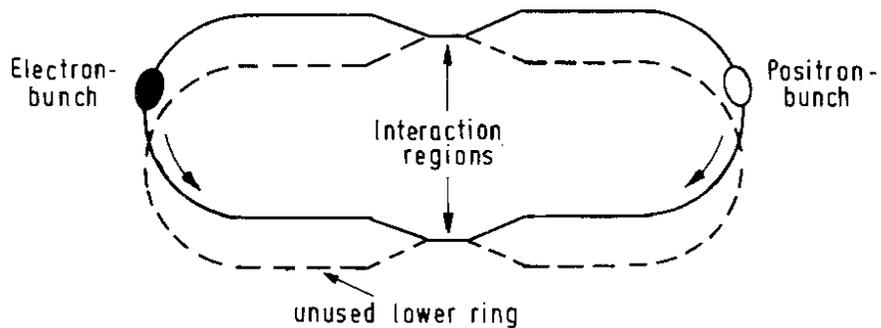of a vertical bending section.

Fig.2 The DORIS single ring concept. The bunches collide head-on although
a modified vertical bending still takes place due to the fixed position
of the experiments.

In order to achieve sufficient accelerating voltage at 5 GeV the original
DORIS cavities had to be replaced by the five-cell cavities developed
for PETRA. These cavities have a six times higher shunt impedance than
the DORIS cavities.

At energies above 4 GeV the saturation in several magnets increases
rapidly. In particular, the high aperture quadrupoles next to the inter-
action points limit the energy in the original DORIS concept. In order
to overcome this limit these quadrupoles were shifted 0.8 m further
away from the interaction points to reduce the required focussing strength.
The saturation of the different magnets during energy variations was
automatically corrected by a computer program so that the orbit and the
tuning of the machine were kept nearly constant. As the energy increases
so do the dimensions of the beam. At an energy of 5 GeV the beam dimensions
are within the same order of magnitude as the apertur. Small beam
oscillations can limit the current, the life time of the beam and the
luminosity. In order to damp these oscillations an electrical fast Feed-
back system was installed. This system worked continously during injection
and storage.

The generation and the handling of the single bunches required modification
of the two linacs, the injection kicker magnets and the timing electronics.

After these modifications had been made to DORIS the following results
were obtained:
Positron injection rates of maximum of 6 mA/minute and electron injection
rates of 15 mA/minute were achieved. During injection no separation plates
were used.
The currents at the beginning of a run for high energy experiments were
approximately 20 mA per beam and the resulting luminosity was about 1×10^{30}
$cm^{-2} sec^{-1}$ at the center of mass energy of 9.5 GeV. The maximum energy at
which luminosity was generated was 10.1 GeV and limited by the rf-power.

2. The new vertical bending section

The two high energy detectors DASP and PLUTO have a fixed position and it
was therefore necessary to maintain the vertical bending on both sides
of the interaction regions. Fig. 3 shows a comparison of the vertical
bending in the double ring and in the single ring.
In the single ring the beams pass the interaction quadrupoles on axis, i.e.

without vertical bending. The beam then passes through a weak dipole magnet with a large vertical bending radius of 59.6 m. The adjacent quadrupole with an off-axis orbit has a weak strength of 0.148 m^{-2}. This slight bending around the interaction region leads to a considerable reduction in the synchrotron radiation background compared with the double ring.

The interaction quadrupole would be saturated up to a high degree when operating at 5 GeV.
Hence, the quadrupole strength had to be reduced or in other words the focus length had to be increased. This was affected by the 0.8 m position shift as shown in fig. 3. As a consequence the saturation was reduced to 3,6 % at 5 GeV. A more detailed description of the saturation effects of the magnets will be given later in this report.

Fig.3 Comparison of the vertical bending in the double and the single ring structure
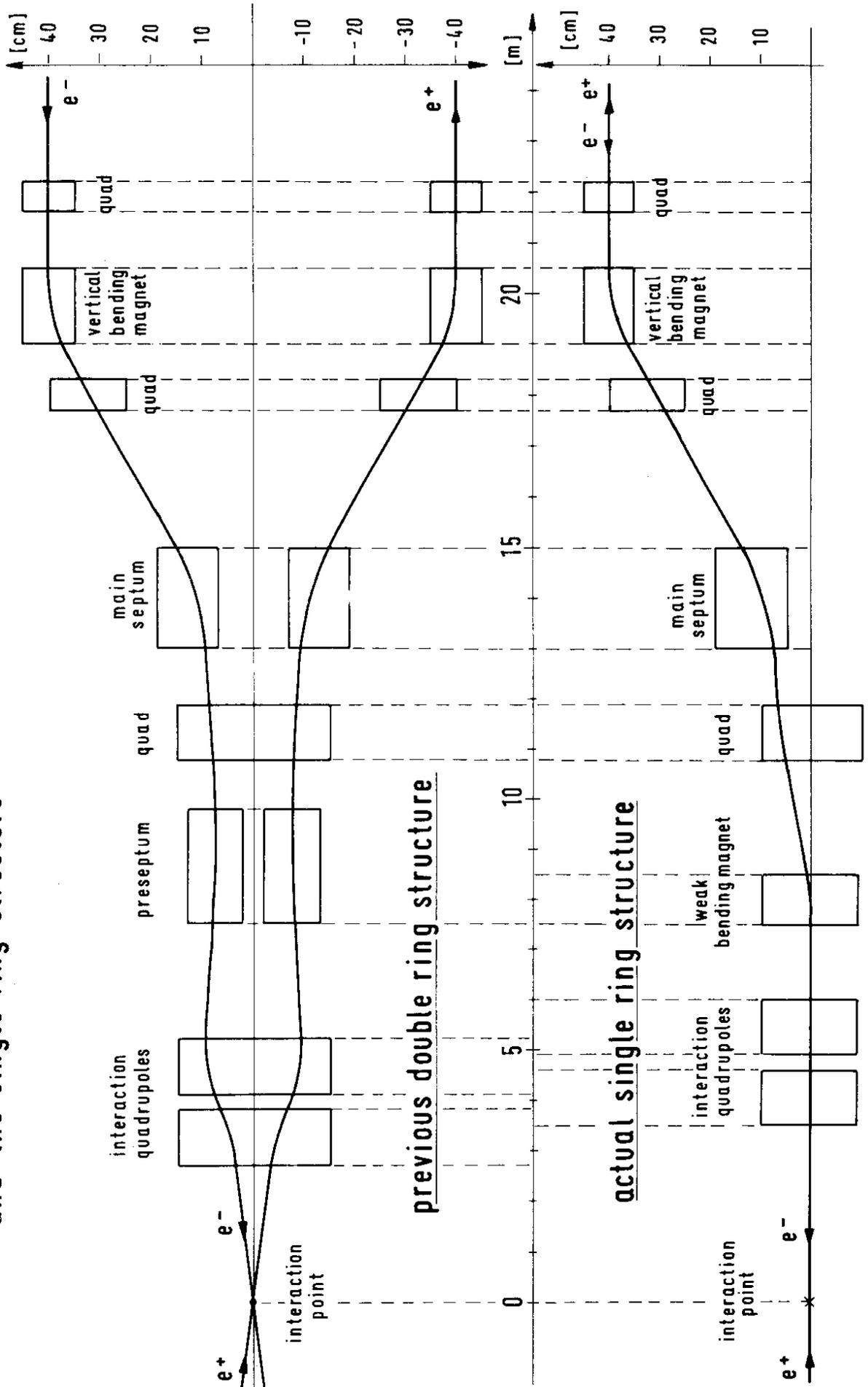
3. Linear beam optics

In choosing the quadrupole strength the following conditions - some of them contradictory - have to be fulfilled. Some of them are especially important with respect to the limited rf-power.

a. Small vertical and horizontal amplitude functions in the interaction point to increase the specific luminosity and to reduce the space charge effect.

b. Small horizontal and vertical dispersion in the interaction point to increase the specific luminosity and to avoid satellite resonances.

c. Small horizontal and vertical beam emittance to increase the specific luminosity. This requirement is equivalent to small horizontal and vertical dispersion in the bending magnets.

d. Low momentum compaction to achieve high beam currents and high beam energy by the rf-power installed.

e. Low chromaticity for the linear machine and a possibility for compensating it by sextupoles.

f. Small maximum amplitude functions to get high acceptance.

g. Good conditions for injection, i.e. a multiple of 180° for the horizontal phase advance between kicker magnets and a large horizontal amplitude function and a small horizontal dispersion at the septum.

h. Working point above an integer.

i. Strength of the quadrupoles as small as possible to minimize saturation effects.

The saturation is defined by

$$S = \frac{B_{ideal} - B_{real}}{B_{ideal}}$$

where B_{ideal} represents the field strength of an idealized magnet which is exactly proportional to the current through the coils and B_{real} the field strength of a real magnet.

The hybrid computer HRS 860 and an optimization program on the IBM 390-168 were used to solve this problem. The following results were obtained:

a. Amplitude function in the interaction point:

$$\beta_{xo} = 1.19 \text{ m}$$
$$\beta_{zo} = 0.28 \text{ m}$$

b. Dispersion in the interaction point:

$$D_{xo} = - 0.68 \text{ m}$$

$$D_{zo} = - 0.07 \text{ m}$$

c. Horizontal emittance for 1 STD (standard deviation) at 1 GeV:

$$\varepsilon_x = 0,023 \text{ } \pi \text{ mrad mm}$$

coupling between vertical and horizontal betatron oscillations as measured:

$$\frac{\varepsilon_z}{\varepsilon_x} = 0.015$$

Dispersion in the bending magnets:

$$0.51 \text{ m} \leq D_x \leq 1.41 \text{ m}$$

$$0.01 \text{ m} \leq D_z \leq 0.26 \text{ m}$$

d. Momentum compaction:

$$\alpha = 0.018$$

e. Chromaticity for the linear machine

$$\xi_x = - 15.1$$

$$\xi_z = - 13.9$$

This can be compensated up to 5 GeV by the existing sextupoles

Maximum integrated strength for one single concentrated sextupole

$$m = 1.94 \text{ m}^{-2}$$

f. Maximum amplitude function

$$\beta_x = 67.5 \text{ m}$$

$$\beta_z = 55.3 \text{ m}$$

Maximum dispersion

$$D_x = 2.31 \text{ m}$$

$$D_z = 0.26 \text{ m}$$

Measured acceptance

$$A_x = 38 \text{ } \pi \text{mrad mm}$$

$$A_z = 12 \text{ } \pi \text{mrad mm}$$

g. Phase advance between kicker magnets

$$\phi_x = 564^{\circ}$$

Hor. amplitude function at the septum

$$\beta_x = 15.9 \text{ m}$$

Hor. dispersion at the septum

$$D_x = 1.73 \text{ m}$$

h. Working point

$$Q_x = 7.16$$

$$Q_z = 5.28$$

i. The strength and the saturation for the different types of magnets is:

α) The field strength in the bending magnets is determined by the radius of the closed orbit: 13.7 kΓ at 5 GeV at a saturation of 8 %.

β) The strength of the large aperture (d ≃ 269 mm) quadrupoles near the interaction points could be limited to $k = 0.563 \text{ m}^{-2}$ with a saturation of 3,6 %. The corresponidng field strength at the poles is 12 KΓ.

γ) A strength of $k < 0.8 \text{ m}^{-2}$ was choosen for the remaining quadrupoles (d = 160 mm). The field strength at the poles is < 10.6 KΓ and the saturation $\leq$ 3 %.

Fig. 4 demonstrates the advantage of these optics at 5 GeV over the old double ring optics regarding the saturation effects.
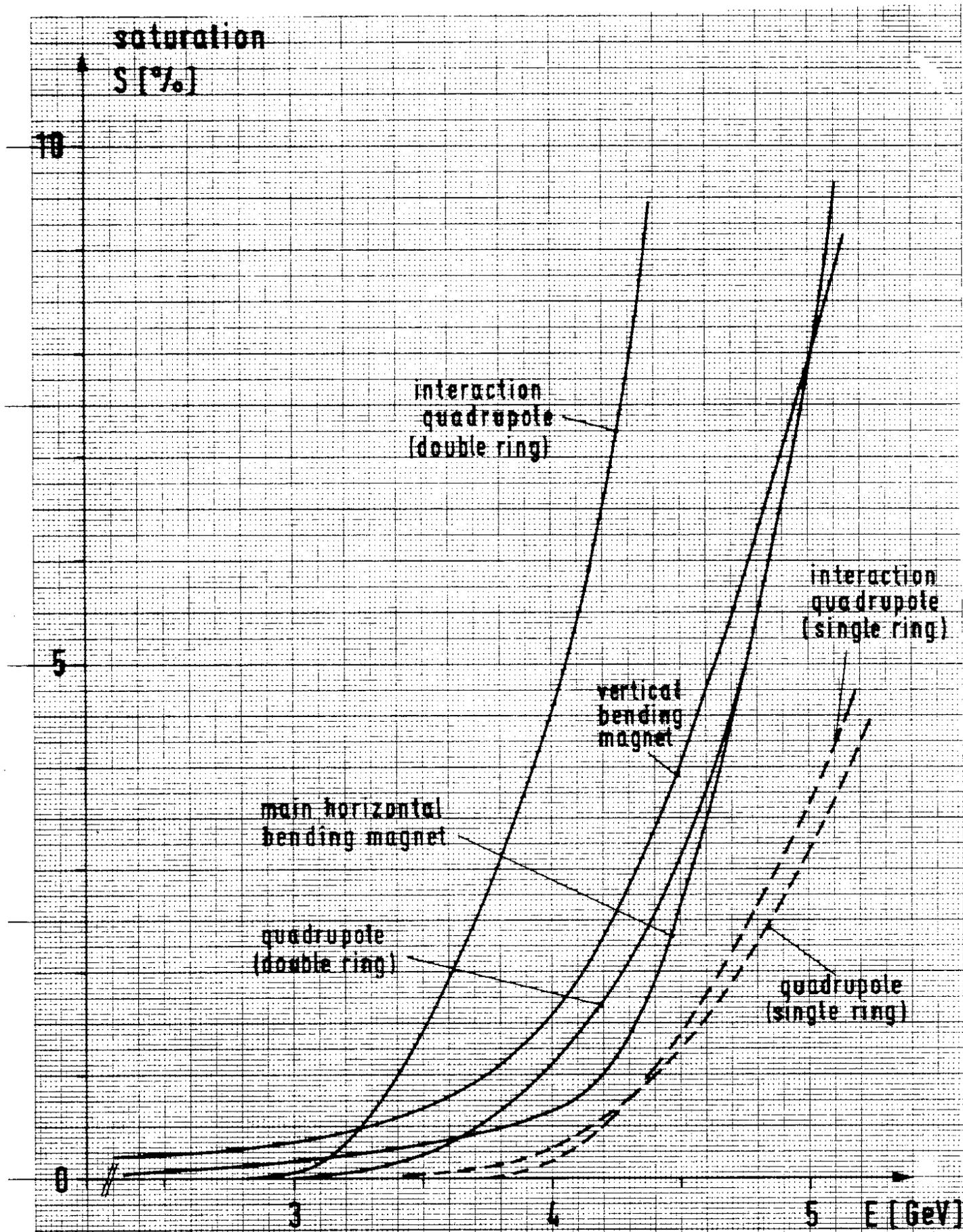
Fig. 4. Saturation of the most excited magnets in the double and the single ring structure

4. The numerical correction of the saturation effects

The correction of the saturation effects is done by the DORIS-computer.
The exitation curves are stored in the computer in the form of measured
values. The distance between two measured values is 50 A. The calculation
of the saturation corrections is demonstrated in fig. 5 for a single
magnet. If the energy is increased from let us say 3 GeV to 5 GeV the
current of the magnet must be altered nonlinearly. Firstly, the current
needed for 5 GeV is calculated (B). Without intermediate corrections the
path between A and B is given by the dashed line. Following this line the
Q-value of the machine would change and this could be hazardous for the
beam. Therefore, in a second step, intermediate points (C, D, E ...)
on the actual curve are calculated and the current is linearly inter-
polated between every two points.

In practice all the magnet circuits have to be changed in the above mentioned
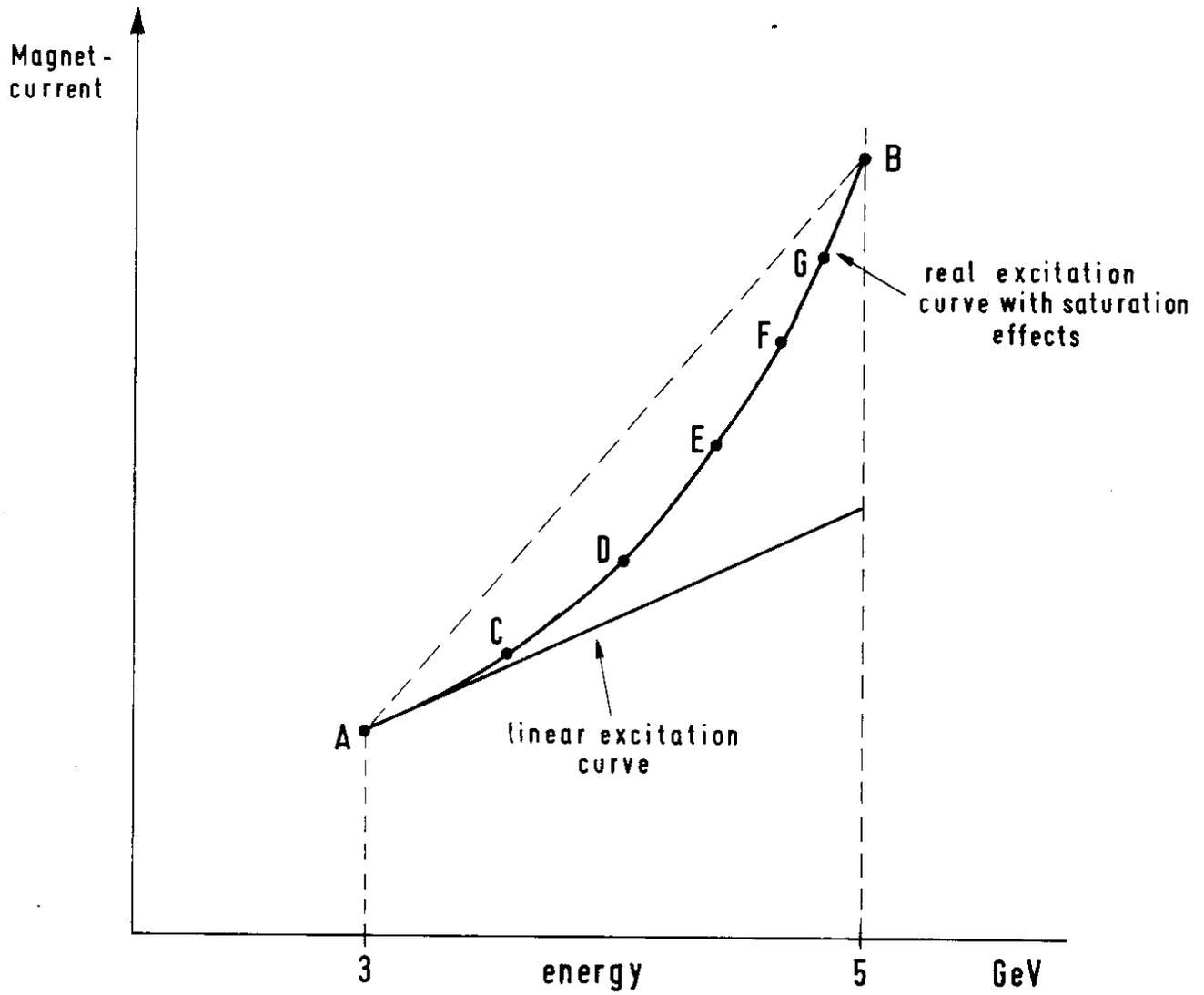way.

Fig. 5 Demonstration of the correction program for the saturation effects. The machine follows the real excitation curves by employing several bases (C, D, E, F, G)

5. Chromaticity correction

In order to stabilize the beam against the head tail effect, the chromaticity in DORIS was compensated by sextupoles. To avoid strong nonlinearity in the particle motion caused by high sextupole strengths, sextupole windings in quadrupoles were used in addition to strong sextupole magnets. This resulted in a more even distribution of the nonlinear fields.

These additional sextupoles in the horizontal and vertical focusing quadrupoles are connected to one power supply each. Two further sextupole circuits consist of strong sextupole magnets which are located at positions of large horizontal resp. large vertical betafunctions (Fig. 6).

The arrangement of sextupoles for minimum higher order perturbation of the linear motion was found in two steps with a tracking program.

Firstly, the maximum stable emittance for a given Q-value was found as a function of the four sextupole strengths. Secondly, the influence of the intrinsic resonances near the working point for the given distribution and the amplitude-dependent effects of the second order were investigated.

The following conditions must be fulfilled:

1. $\xi_x = 0;$ $\xi_z = 0$ the linear chromaticity must be compensated

2. The maximum integrated sextupole strengths for the sextupole windings in one quadrupole at 5 GeV may not exceed 0.33 (m^{-2}). Otherwise the temperature in the coils would become too great.

The maximum stable particle emittances for different Q-values are drawn in the diagram (fig. 7) for the optimum sextupole distribution.

Saturation effects in the bending magnets at higher energies necessitate a correction of the sextupole strength (fig. 8). These relatively small effects were compensated empirically.
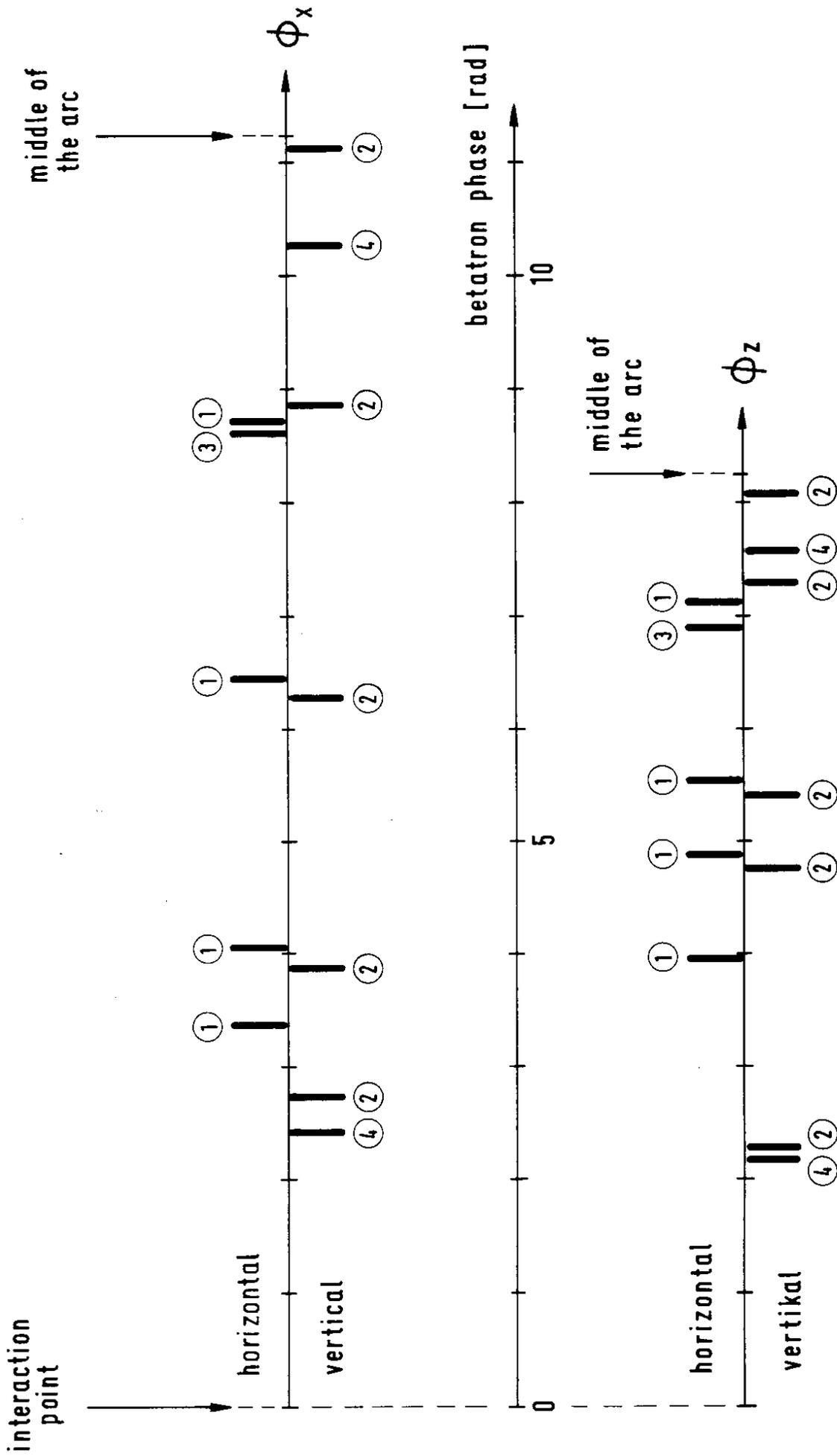
Fig. 6: Distribution of the additional sextupole windings in the quadrupoles (1 and 2) and the strong sextupoles (3 and 4) vs. betatron phase. (Sextupole windings denoted by the same number are connected to one power supply)
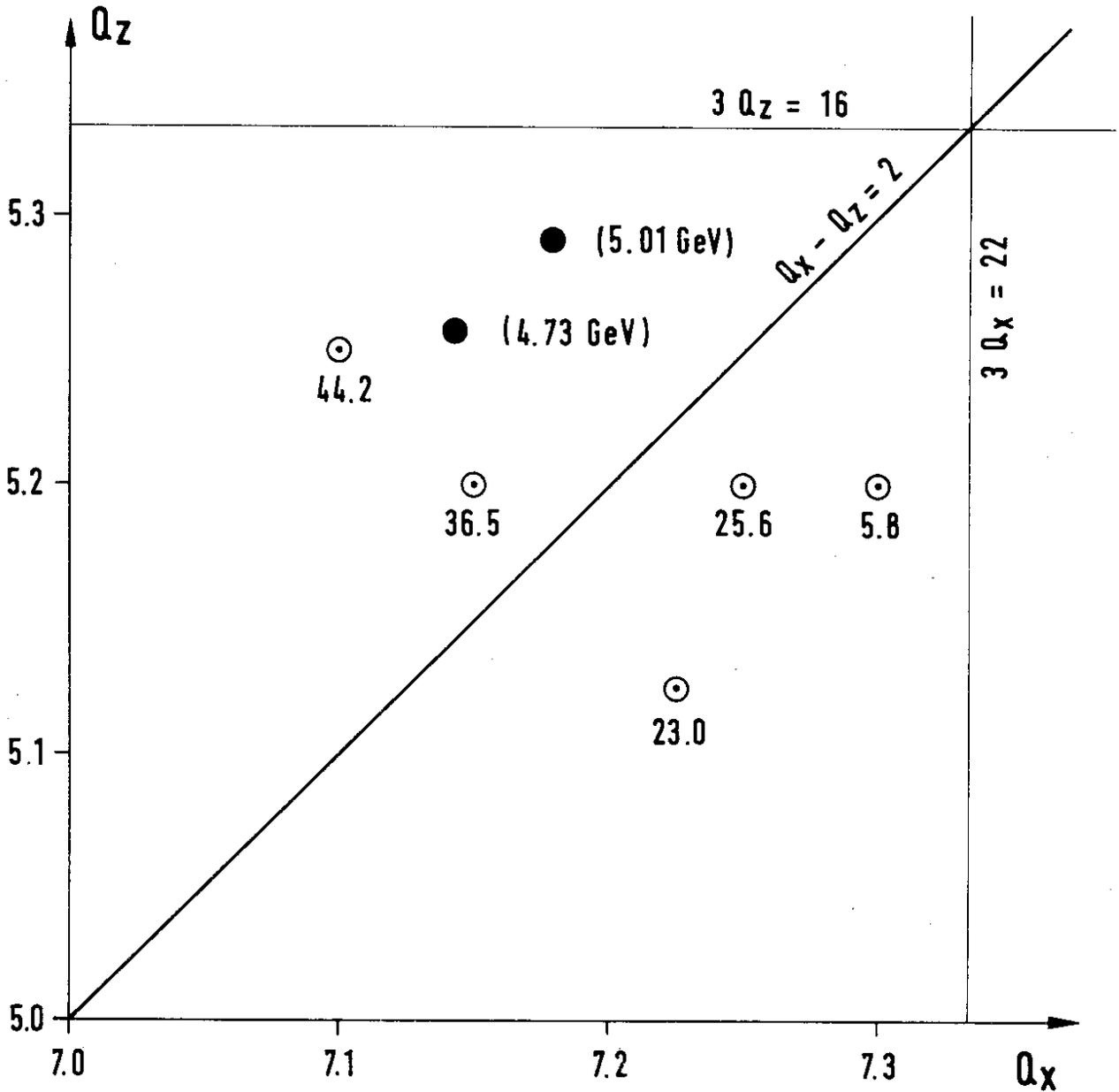
Fig. 7 Calculated maximum stable horizontal emittances
for different Q-values (in π mm. mrad)
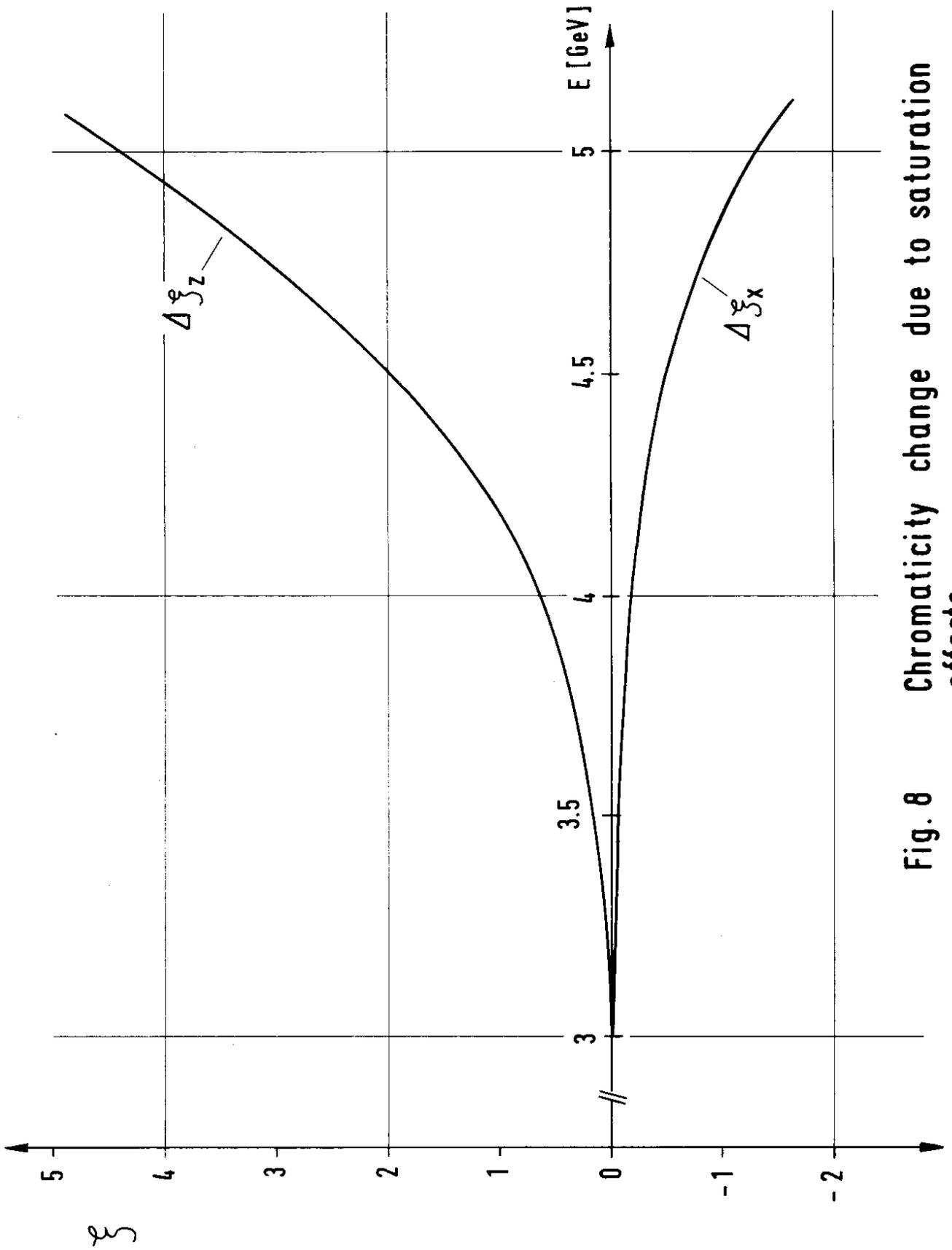(● choosen working points)

Fig. 8   Chromaticity change due to saturation effects

6. Estimation of the energy error

The error margin regarding energy is due to the following points:

a) Uncertainty about the relation of the current and the field strength in the bending magnets

b) Kicks given to the beam either by closed orbit correction coils or by quadrupoles and sextupolesbeing passed off axis by the beam.

The change in energy due to kicks is given by

$$\frac{\Delta p}{p} = \frac{\sum_i \delta_i D_i}{\alpha L} \tag{1}$$

with δ_i i-th kick

D_i dispersion at the kick

α momentum compaction

L   length of the closed orbit

The uncertainty about the relation between current and field strength is 10^{-3} for the bending magnets in the region of saturation. Formula (1) yields $\frac{\Delta p}{p} = 4 \cdot 10^{-4}$ for the actual kicks of the correction coils at the Y-resonance energy. To estimate the effect of the quadrupoles it is assumed that the beam at all quadrupoles is 5 mm away from the axis and that the dispersion is 1 m. This yields $\frac{\Delta p}{p} = 1.5 \cdot 10^{-4}$. The influence of the sextupoles has been taken into account by doubling this value. Summing up all effects the most probable error in beam energy is $\pm 1.1 \cdot 10^{-3}$ or $\pm$ 5 MeV at the Y-resonance energy.

7. RF-system for single ring operation of DORIS

To increase the energy of DORIS as a two bunch single ring, from 3 GeV to the Y-region, it was necessary to modify the rf-system. The original 12 single cell DORIS cavities were replaced by 8 inductively coupled five cell PETRA cavities[13] with a shunt impedance of 18 MΩ per cavity. Each is driven by 125 kW rf-power. This increases the accelerating peak voltage up to 16 MV. The cavity tuning equipment was also modified as described in [13] so that the five cell cavities can be frequency-matched.with regard to beam-loading and temperature effects with two tuning plungers only. With this modification it was possible to achieve a maximum beam energy of 5.1 GeV with luminosity.

The arrangement of the 8 five cell cavities in DORIS is shown in fig. 9.

The main parameters of this modified rf-system are given in the table below.

In the double ring operation a decoupling of cavities and klystron amplifiers was done by a special arrangement of the waveguide-transmissionline components[14]. In the single ring operation with particles passing through the cavities in both directions, decoupling is only possible by means of rf unilines which were not available. So the rf-system in the single ring operation is driven without decoupling. Since a reflection of more than 20 kW towards the klystron is not permissible, a fast modulation loop which acted on the klystron modulation anode was installed in the amplifier to avoid switching off of the rf as a result of small beam losses or ionisized gas desorption in the cavity.

Table: Main rf-parameters for the single ring operation of DORIS at high energies

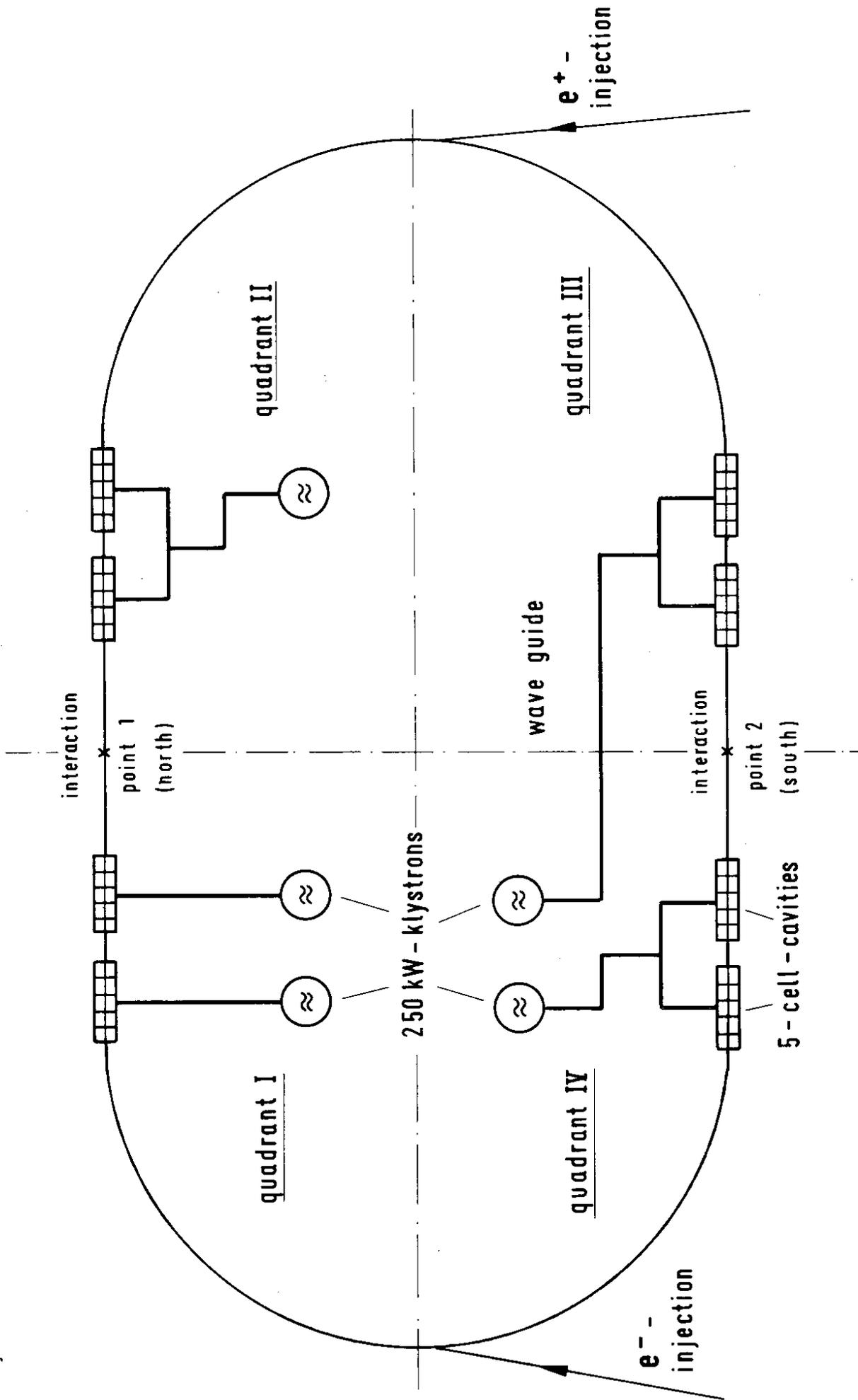| Particle energy	$E\,(\text{GeV})$	5.1
No. of PETRA cavities		8
Radiation loss	$U_r\,(\text{MeV})$	4.77
Synchronous phase angle	$\Phi_s\,(\text{deg})$	27.5
Peak acc. voltage	$\hat{U}_c\,(\text{MV})$	11.9
Total rf-power	$P_{HF}\,(\text{kW})$	1000
Dissipated power in cavities	$P_c\,(\text{kW})$	495
Beam power	$P_b\,(\text{kW})$	410
Power due to parasitic modes	$P_{PM}\,(\text{kW})$	54.0
Additional rf-power (waveguide loss, mismatch etc.)	$P_L\,(\text{kW})$	100
Total rf-limited beam current	$2 \times I_b\,(\text{mA})$	73.5

Fig. 9   Arrangement of PETRA - cavities in DORIS for single ring
operation at 5 GeV

8. Vacuum system

Extensive modifications in the vacuum system were needed to permit the single-ring operation. The upper half-rings had to be modified to account for the additional beam now circulating in reverse direction in a common vacuum chamber.

Additional chambers were needed for the new magnets in the vertical bending regions and for several components which had to be redistributed along the ring to place them in radiation-protected regions. Some measuring devices from the inactivated sections also had to be moved to the upper ring.

The main task was to protect all components and vacuum chambers with watercooled synchrotron radiation absorbers. The protection of the vacuum chamber against direct synchrotron radiation is necessary since the vacuum chamber consists of stainless steel with low thermal conductivity. Additional requirements were: minimum cost, installation of the new elements in a relatively short shut-down period, and the possibility of easily reconverting to double-ring operation.

All new absorbers were designed to provide adequate cooling for a synchrotron radiation thermal load of 180 kW from each circulating beam (2 x 40 mA at 5 GeV).

Special absorbers were developed to avoid extensive modifications in the vacuum system. Some were mounted on intermediate flanges with integrated water feedthroughs and others were designed as watercooled gaskets compatible with the flange system. In this way it was possible to prepare and test most of the additional protection devices before the shutdown period, so that the actual in situ work was mainly limited to the installation of the new components and absorbers in existing chambers.

9. Power supply and cooling

For an operation at 5 GeV the water quantities had to be adapted to the needs of the new system by increasing the pressure from 6 to 12 bar. But even with this high pressure the operation temperature of the magnets had to be increased up to 75° C and the threshold for the thermal interlock from 75 to 90° C.

Instead of the original DORIS power supply for the bending magnets, a new power supply was used. With this power supply the currents could be increased by a factor of 1.55 as compared with the original power supply. As a consequence of the new optics most of the other power supplies had to be

recabled due to the alterad loads.

10. Generation and injection of single bunches

The Linac I – Linac II – DESY – DORIS arrangement is sketched in fig. 10.
The synchrotron DESY is used as the injector for DORIS. With the old DORIS
concept all accelerators including the linear accelerator Linac I and
Linac II, the synchrotron DESY and the storage ring DORIS, worked with a train
of electron and positron bunches. In the synchrotron an rf-system with an
frequency of 500 MHz was used and the time interval between two bunches was
2 nsec. With DORIS as a single bunch storage ring the multibunch trains
have to be reduced to a single bunch. The single bunch selection is done
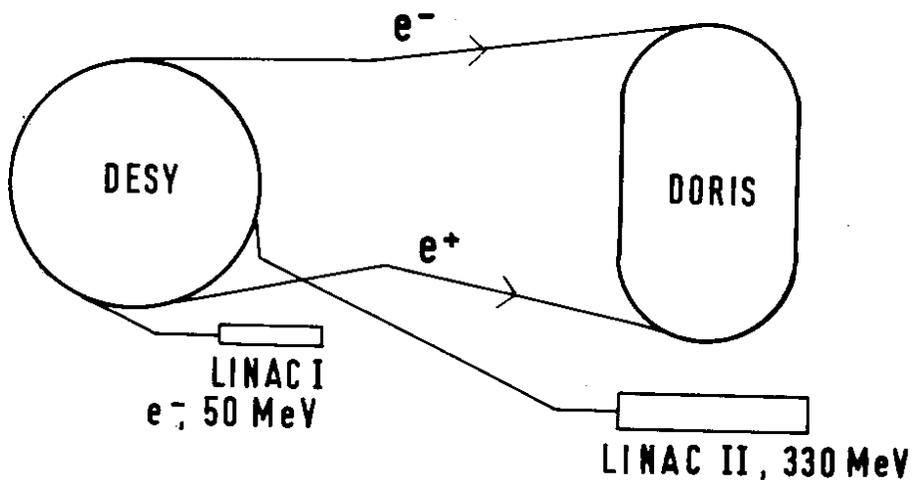in front or behind the linacs.

Fig. 10

Linac I is a 50 MeV linac for electrons. At the end of this linac a so-called Post Linac Chopper was installed[18] (fig.11) consisting ot two orthogonal deflecting plates and a pair of collimator slits. The first pair of plates is connected to a 62.5 MHz transmitter and the second to a thyratron - switched high voltage power supply. The first pair of plates are effective in producing a bunch train with a distance of 8 nsec. With the second pair of plates a single bunch out of the 8 nsec bunchtrain containing about $1.5 \cdot 10^8$ particles is selected. Three additional quadrupoles were installed between the deflecting plates and the slits to increase the effectiveness of the whole system. A Post Linac Chopper has the advantage over a chopper near the gun that the energy of a pulse train and a single pulse emerging from the linac is identical. Linac I delivers in the so-called beam sharing mode of operation either single bunches for DORIS or bunch trains for other users of the synchrotron according to a predetermined sequence. Using a chopper between gun and linac, the beam loading in the linac structures between a pulse train and a single bunch would be different leading to different energies between pulse trains and single bunches.

Linac II is a 330 MeV linac for positrons. The magnitude of the current of the positrons is proportional both to the energy and the current of the electrons hitting the positron converter target. The maximum electron energy can be achieved by using a single pulse selection system between the gun and the first linac structure (fig.12)[19]. This is due to the fact that the above mentioned beam loading effects are smaller with single bunches compared to bunch trains. At the same time the current of the linac was increased by a factor of 6 leading to a single bunch containing $5 \cdot 10^7$ positrons (analyzed beam $\Delta E/E < 0.5 \%$). As a result the filling times for positrons in DORIS (including the magnet training program) were between about 10 to 20 minutes.
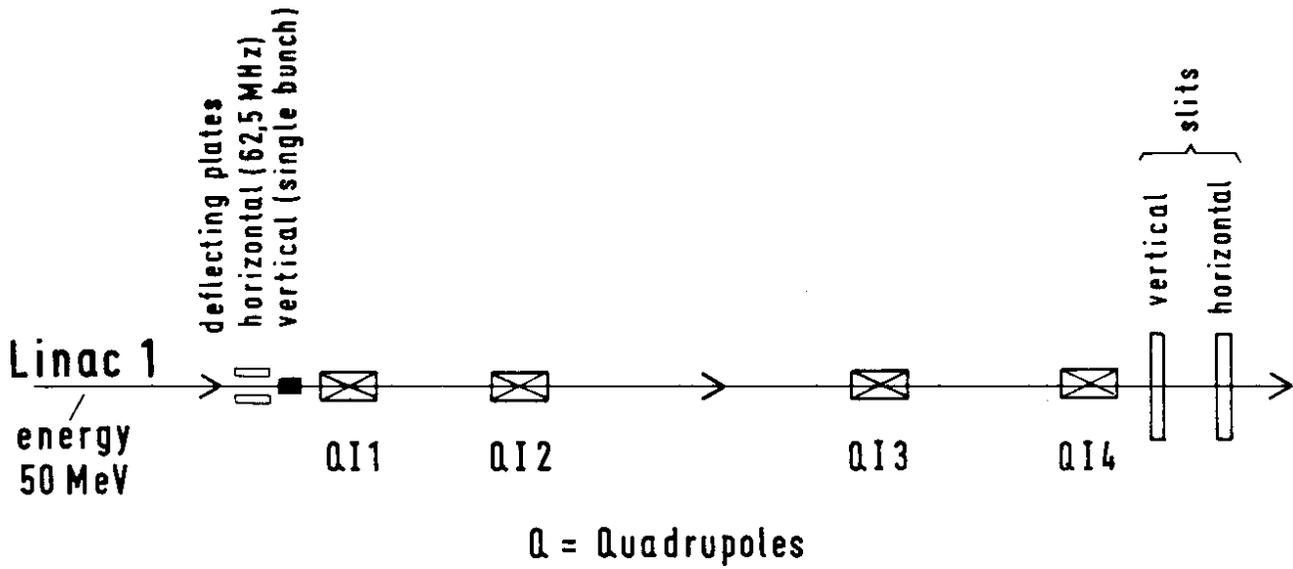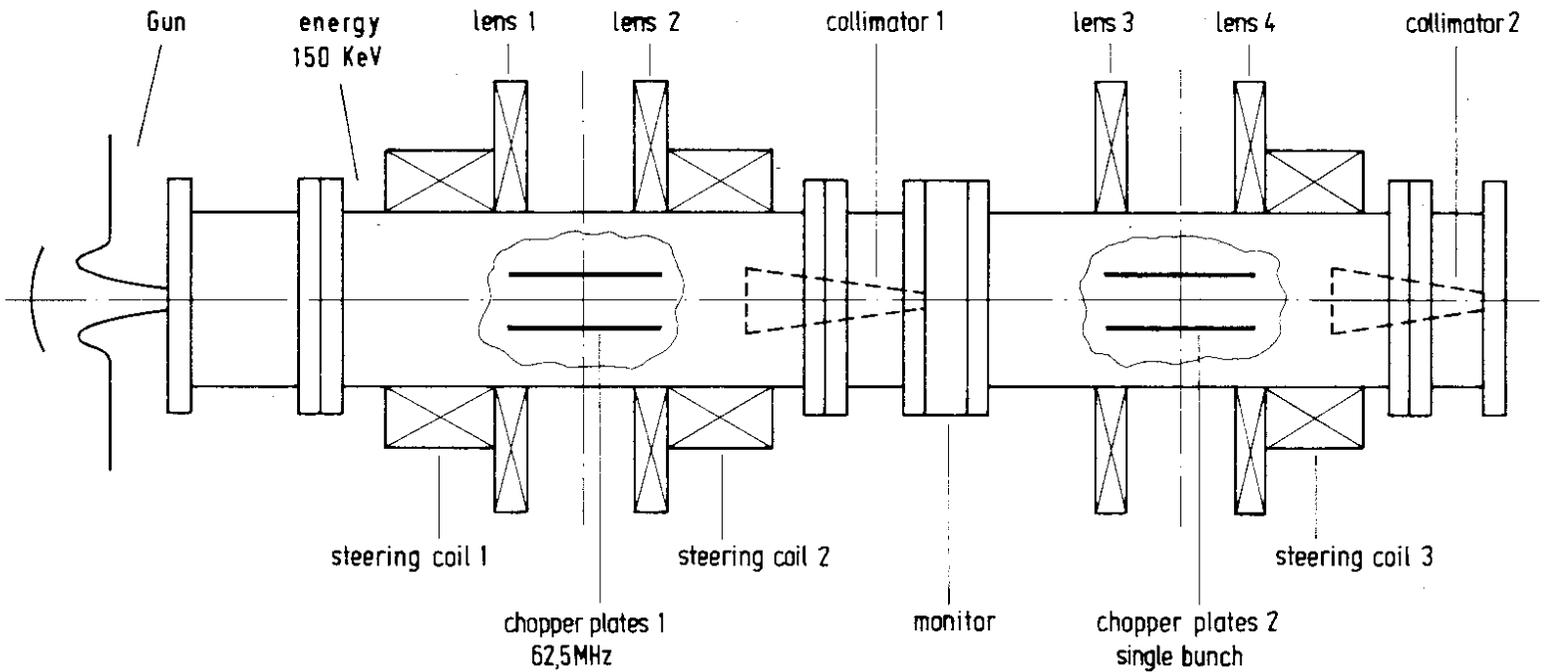
Fig. 11   Post Linac Chopper

Fig.12   Linac II - injection system

DESY. The repetition frequency of the linacs and the synchrotron DESY is 50 Hz. One acceleration period is therefore 20 msec. The two linacs operate as follows: linac I delivers one e^- bunch for each fourth acceleration period and linac II delivers e^+ bunches during the remaining three periods.[25]

The ratio of the circumferences DESY/DORIS is 11/10. In order to accumulate a single bunch in DORIS it is necessary to eject the bunch from DESY after a fixed number of revolutions. Changing the ejection energy means changing the number of revolutions in the synchrotron. In order to hit the same bucket as before in DORIS the number of changed revolutions has to be a multiple of 10. To achieve high injection rates it is necessary to change the energy in steps of less than 10 revolutions (corresponding to approximately 10 MeV). In this case the bunches have to start at the linacs at different times. This complicated timing problem was solved with the help of so-called bunch trigger generators[23]. These trigger generators have an extremely low time jitter and allow the desired buckets to be selected.

The transportation and acceleration of single bunches requires a modified monitor system.

A so-called resistive wall monitor[21,22] connected to a scan converter was installed. A single bunch passage with more than $3 \cdot 10^4$ particles through the monitor could be measured.

Beam profile and position can be observed by ZnS_2-screens in connection with tv-cameras. The sensitivity has been increased by placing a 15 mm thick lump of lead in front of the fluorescent layer.

11. Single beam instabilities observed

1. Coherent instabilities

The following instabilities were observed:

a) longitudinal

The longitudinal instabilities were interpreted as coherent phase oscillations due to parasitic modes of the PETRA accelerating cavity. The threshold was observed at about 15 mA average current. This instability was only observed when an electron and a positron beam were simultaneously stored.

A proper tuning of the cavity and correct adjustment of the cavity-transmitter control system avoids coherent phase oscillations up to 50 mA average current.

b) transverse

Horizontal and vertical coherent instabilities were only observed when an electron and a positron beam was simultaneously stored. The threshold was between 12 and 17 mA.

The instability is caused by the parasitic deflecting modes in the PETRA cavities. Since the total width of the parasitic resonances is about 40 kHz a detuning of the cavities away from these modes would reduce the rf voltage to too small a value.

On the other hand, the Q-values cannot be changed by 40 kHz as this would impair injection efficiency and shorten beam life time during the run. However, the horizontal and vertical feedback systems designed for the single ring mode of DORIS completely prevent the transverse instabilities (see chapter 12).

2. Bunch lengthening

Using a high speed photodiode[16] the bunch length was measured as a function of bunch current (fig.13) at 3.5 GeV and an rf voltage of 2.8 MV. This measurement shows that the lengthening factor R remains below 2 at currents of 25 mA/bunch. At 4.5 GeV the bunch lengthening was measured during the luminosity runs. No significant lengthening was detected between 10 mA and 23 mA/bunch.

3. Higher order mode losses

The higher order mode losses were measured by observing the phase shift of the center of bunch charge with respect to the phase of the master oscillator of the rf-system as a function of current (fig.13).

This measurement was performed at 3.5 GeV with 8 DORIS cavities and 2 PETRA cavities.

From these data and the theory of cavity losses[17] it could be concluded that the power dissipated in the vacuum chamber was less than 12 kW for a current of 25 mA in one bunch.
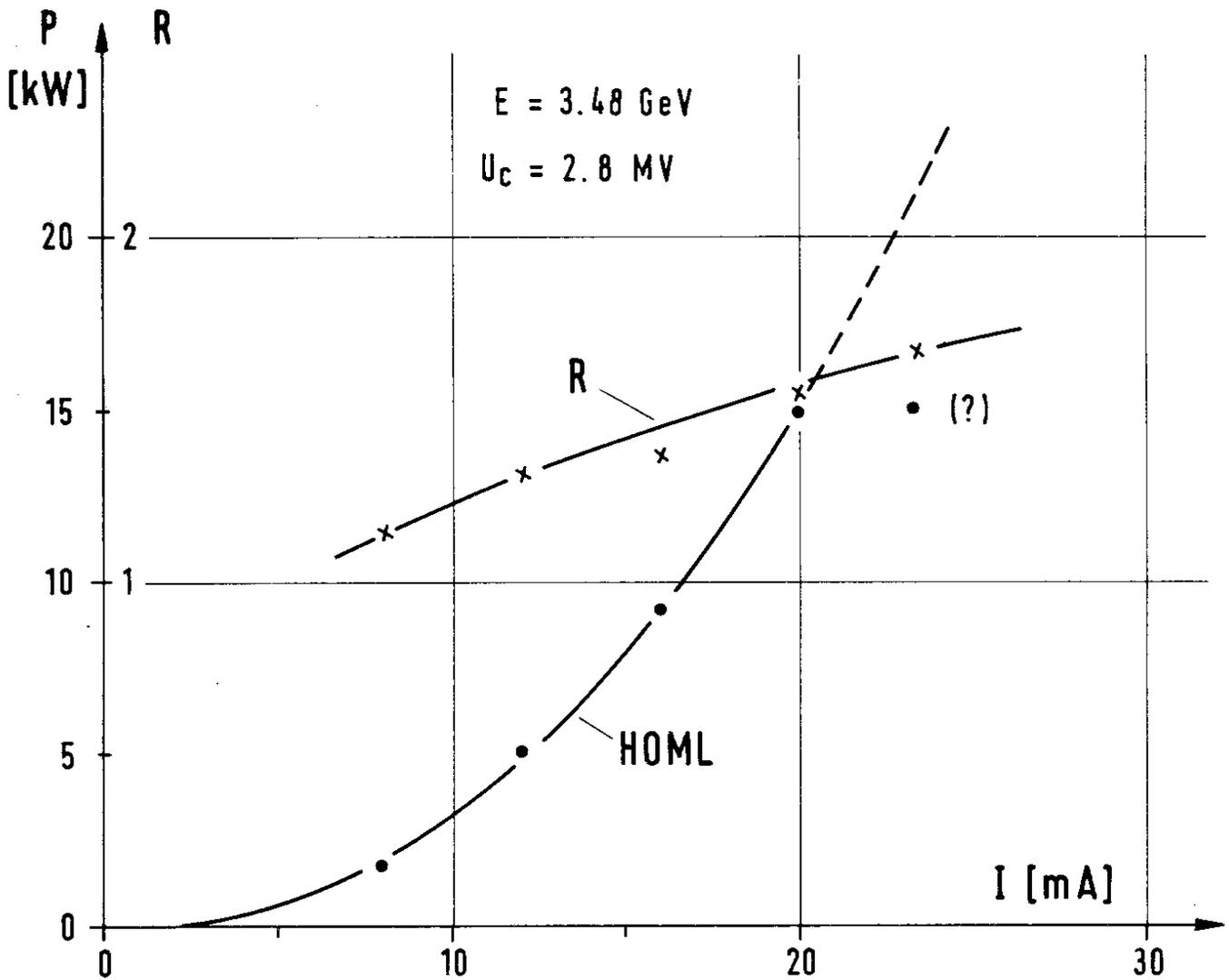

Fig. 13   **Higher order mode losses (HOML) and lengthening factor R as a function of bunch current**

12. Damping of coherent transverse instabilities by a feedback system

1. Transverse instabilities

Coherent transverse instabilities limit the maximum average current of the
two bunches in the single ring structure. The instability limit depends
on the sum of both beam currents and is almost independent of the ratio
of the two bunch currents. The instability threshold is between 15
and 25 mA and depends mainly on the tuning of the cavities and the
working point of the machine. The coherent damping factor $\alpha = 1/\tau$
(τ = damping time) versus beam current is shown in fig. 14.

In order to damp these coherent transverse beam oscillations and to
achieve higher currents a narrowband bunch-by-bunch feedback system was
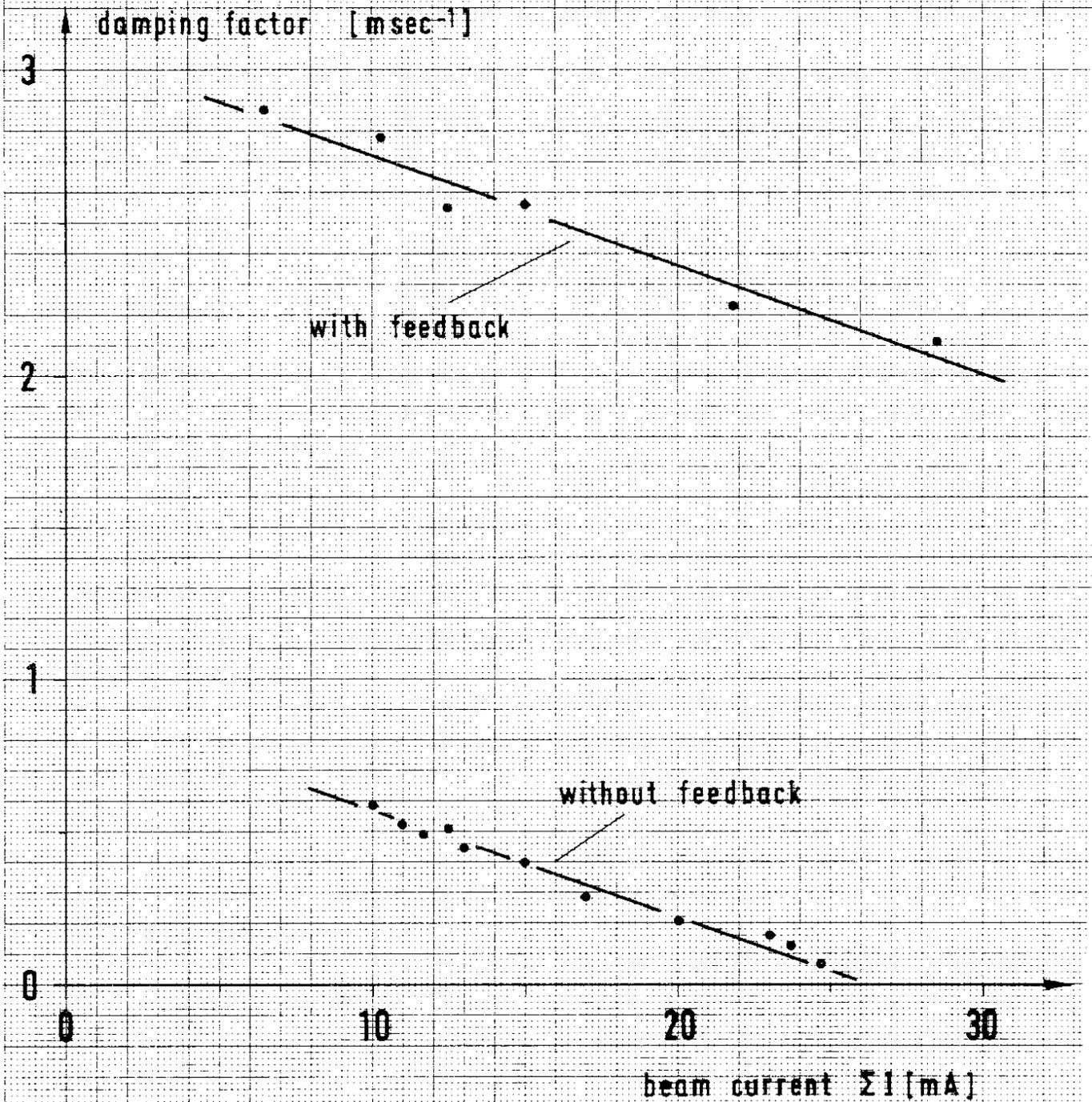installed.

2. Principle of the feedback system

The essential components of the feedback system are shown in fig.15. The
pick-up loops of a position monitor mounted in the middle of the DORIS arc
region sense the betatron oscillations as amplitude modulation of the
bunch signal. There are two pulses per revolution induced alternatively
by the two bunches with a constant time distance of 0.48 μs. Since each
bunch is an independent oscillator the two bunches have to be treated
indepently by the feedback system. The two signals are separated by a
fast switch and conducted to two parallel narrowband electronic detectors.

These electronic detectors generate signal voltages proportional to the
transverse displacement of the bunches from the equilibrium orbit. The
following electronic phase shifters allow adjustment of the signal phase in the
loop.
The beam oscillations are damped with the help of a fast pulsed 0.3 Γm
kicker magnet consisting of an air coil with four windings. The bunches
can be excited independently as the kicker pulses are short compared with
half the revolution time of the bunch. Just before a bunch passes the
pulsed magnet the fast power pulser is modulated with the corresponding
oscillation signal by using another fast switch which samples the outputs
of the two phase shifters .

Fig.14 Damping factor of horizontal coherent beam oscillations measured at DORIS at an energy of 4,6 GeV
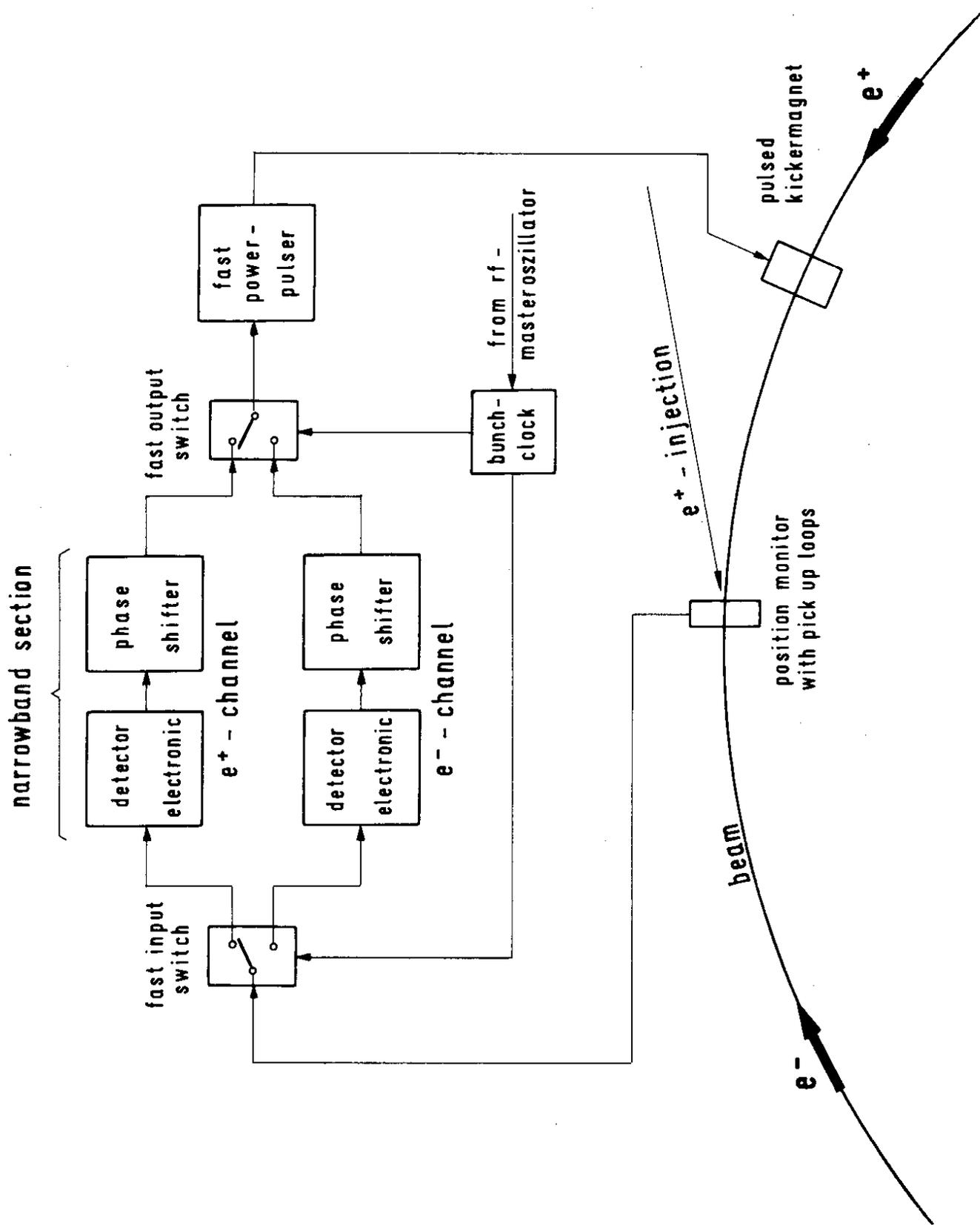
Fig.15   Principal arrangement of the transverse feedback system

The two individual feedback loopes described above allow damping of all
coherent transverse oscillation modes. Two identical feedback systems
are installed to damp the horizontal as well as the vertical oscillations.
The narrowband technique provides high sensitivity with low noise.
To maintain the required luminosity in normal experimental runs it was
necessary to accumulate currents above the instability threshold and
to keep the feedback system in continous operation. The resulting damping
factor is shown in fig. 14.

The oscillations occurring at injection and the transverse instabilities
could both be damped with this system.

13. Beam-Beam Interaction

The maximum luminosity is not limited by the beam-beam effect as in the
case of the double ring with a crossing angle[9]. For the single bunch operation
a splitting of the synchrotron and betatron frequencies is not necessary
and the satellite resonances can be avoided by choosing a working point
between the resonances. Further, the maximum bunch current is limited by the
vacuum and by the rf-power so that a beam-beam limit between the resonances
can not be reached. However, the number of disturbing satellite resonances
increases rapidly with increasing bunch currents. For small currents the
whole region between the first satellites of an integer and the third integer
resonance is free of dangerous resonances. But at large currents the
operation point can be shifted only by ± 0.01 without beam loss. These
satellite resonances can be excited by the large horizontal inevitable
dispersion in the cavities[10] and by the horizontal and vertical dispersion
at the interaction point[9],[11].
The maximum vertical tune shift is about 0.01 per interaction as in the case
of the double ring with a crossing angle. The tune shift can be measured
directly. The betatron frequency is excited weakly and the coherent signal is
measured with a loop. Fig.16 shows the two eigenfrequencies of the two bunches
which are coupled by the space charge forces. The difference in the frequnecies
is the coherent tune shift per ring.[12] Fig.17 shows the dependance of the
horizontal and vertical coherent tune shifts per ring on the bunch currents.
These measurements give both the vertical and the horizontal tune shift and
the bunch width and height at the interaction point, whereas the luminosity
measurement delivers only the vertical tune shift and the beam cross section.
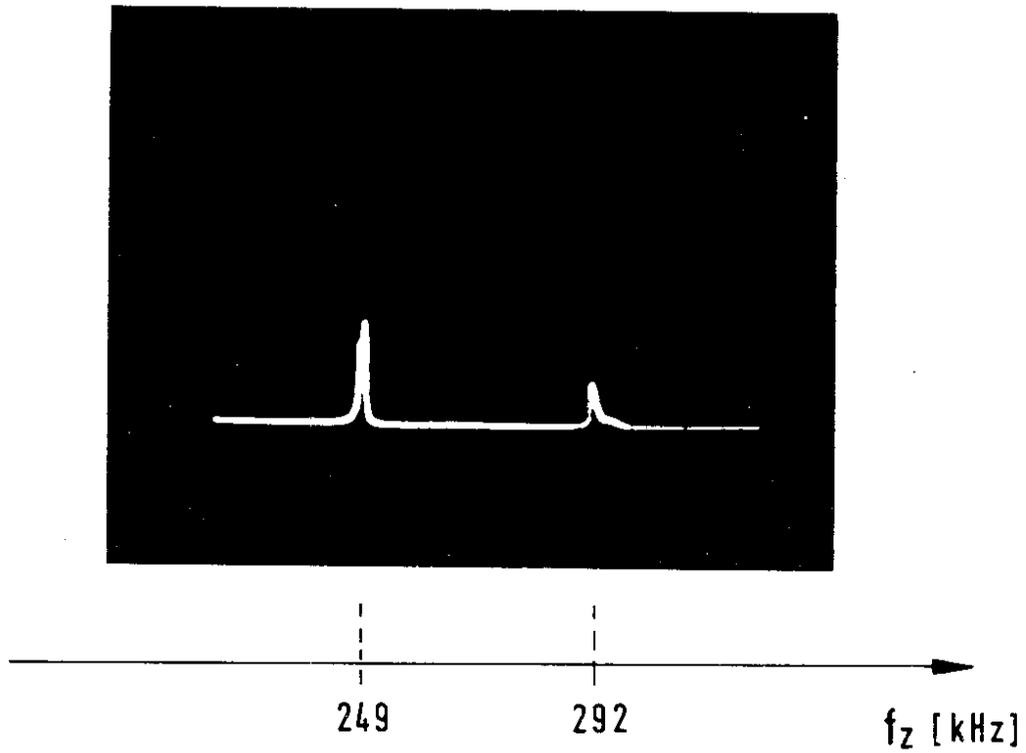
Fig.16   Splitting of the vertical betatron frequency
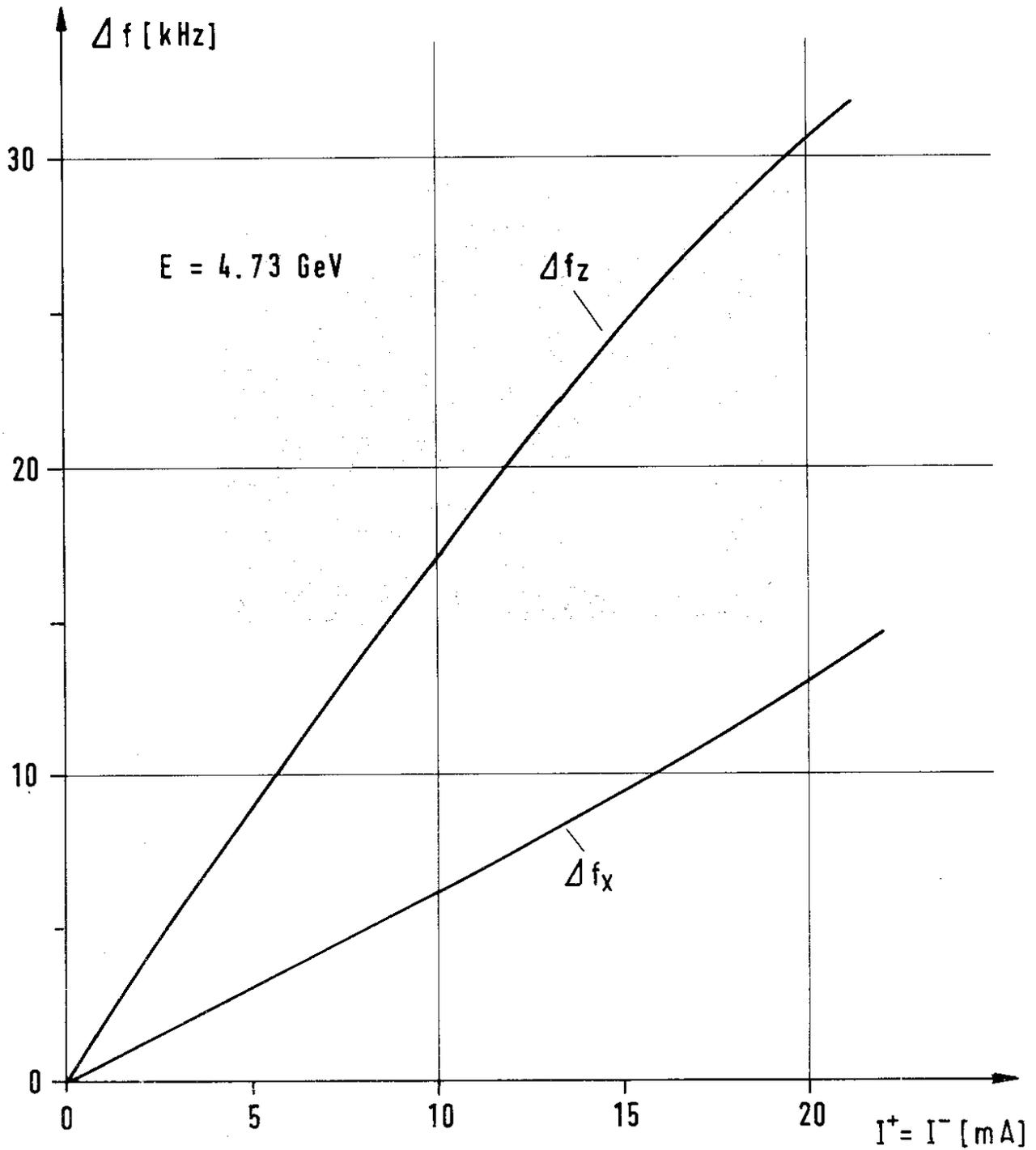due to the beam - beam interaction
(energy E = 4.6 GeV)

$\Delta f [kHz]$

30

$E = 4.73\ GeV$

Δf_z

20

10

Δf_x

0

$0 \qquad 5 \qquad 10 \qquad 15 \qquad 20$

$I^+ = I^- [mA]$

Fig. 17 Dependence of the coherent tune
shifts on the bunch current with two
interaction regions

14. Dispersion in the cavities and its consequences

Since the energy loss per revolution for one particle is in the same order of magnitude as the energy spread of the beam, the change in energy in the cavities has a strong influence on the orbit. The calculation has shown[15] that the orbits are distorted mainly by the dispersion in the cavities. The nonvanishing dispersion in the cavities is due to the fact that the best beam-optics for the single ring under the given circumstances had to be evaluated. As mentioned above, some compromises had to be made and such a compromise is the nonvanishing dispersion in the cavities. The orbit distortion has opposite signs for the two beams and leads to a separation of the orbits which oscillates around the ring. The centers of mass of the two bunches are separated horizontally by a maximum of about one standard deviation. For particles in the head or in the tail of the bunch the separation is greater by a factor of 2 to 3.

The difference in the orbits leads, as sometimes observed, to different life times of the two bunches even when the currents are equal. Measurements with scrapers show a different decrease in life times when the scrapers are moved into the beams.

15. Luminosity Monitor

At both interaction regions of DORIS luminosity was measured by elastic small angle Bhabha-Scattering. The monitors consist of two detector arms facing the interaction region at an angle of about 8° and use the wellknown compensation scheme[24] to get rid of the effects of geometrical fluctuations of the beam-beam-crossing on the Bhabha-counting rates. The ineleastic background was eliminated by energy cuts using the energy information of lead-scintillator-shower counters. Special precautions were taken to screen photomultiplier tubes from magnetic stray fields created by the big quadrupoles near the interaction regions. The monitor acceptance at interaction point 2 was defined by a 10 x 10 cm^2 scintillator at a distance of 2.18 m from the interaction point. This yields a monitor constant per detector arm of $\sigma_{ee \to ee}$ = 650 nb/E^2 or about 5 events/100 sec at E = 5 GeV for the whole detector at a luminosity of 10^{30} $cm^{-2}sec^{-1}$. Accidental coincidences resulting from elastic beam-gas-scattering were measured by a delayed coincidence technique and were less than 5 % at bunch currents of 2 x 20 mA. Radiative corrections of - 6 % with an energy cut of 0.5 E_{beam} have been taken into account.

16. Operating experience

The first run period at center of mass energies of between 9.35 GeV and 9.47 GeV lasted about four weeks and the second run at center of mass energies of 9.8 GeV and 10.14 GeV another four weeks.

In both runs the injection energy was 4.6 GeV per beam. Before each filling the magnetic field of the magnets was increased up to a field-strength corresponding to 5.1 GeV operation, then decreased to 0.5 GeV and again increased to the injection energy of 4.6. GeV in order to avoid remanence effects. After a careful adjustment of all injection parameters single bunch injection rates of 6 mA/min for positrons and 5 and 15 mA/min for electrons were achieved. The total injection time (magnet training program and filling time) was normally less than 30 minutes. Normally the time interval between two filling procedures was about 2 to 3 hours.

Currents of about 20 mA per bunch were usually stored. At higher currents the gas pressure increases rapidly. As a consequence, the beam life time became less than 2 hours and the background in the experimental areas increases to a very high value. The above mentioned beam limit is lower than the well known beam-beam limit. It is therefore not necessary to separate the two beams by separation plates during injection.

The initial value of the luminosity at the maximum beam currents was about $L = 1 \cdot 10^{30}$ $cm^{-2}sec^{-1}$ and at the end of a run normally about $L \approx 3 \cdot 10^{29}$ $cm^{-2}sec^{-1}$.

The measured luminosities agree within 20 % with the calculated values wherein the horizontal and vertical dispersions at the interaction point are taken into account.

The behaviour of luminosity and currents during a special filling of about 4 hours duration is shown in fig. 18.

The slope of the curve is in good agreement with a $L \sim i^+ \cdot i^-$ dependence. Both bunches had nearly the same current over the whole period.

The integrated luminosity per interaction point for a certain run period is shown in fig. 19. The values have been averaged over one day.
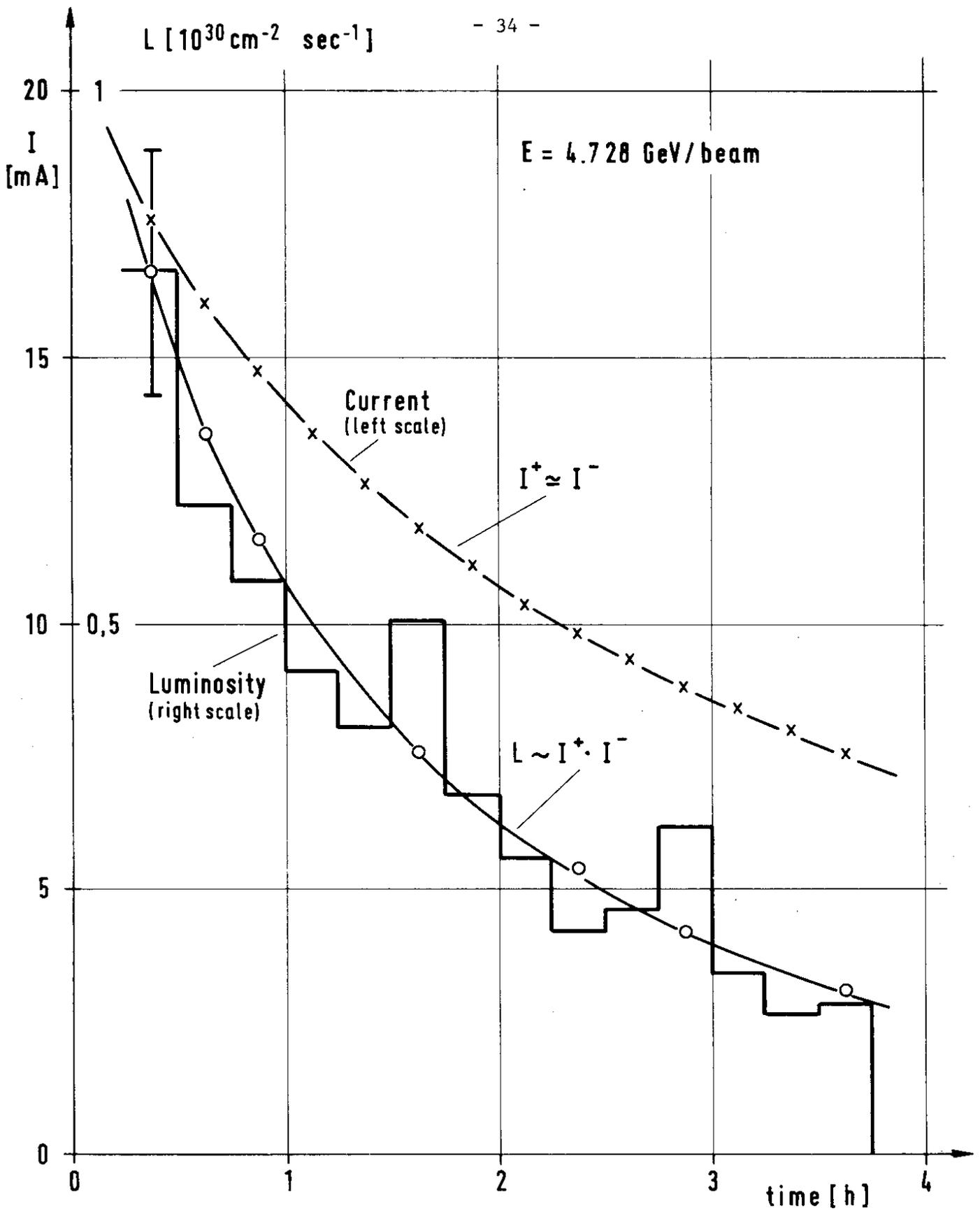
Fig. 18   Luminosity at interaction point 2 and beam currents VS. time (error flag contains only statistics)

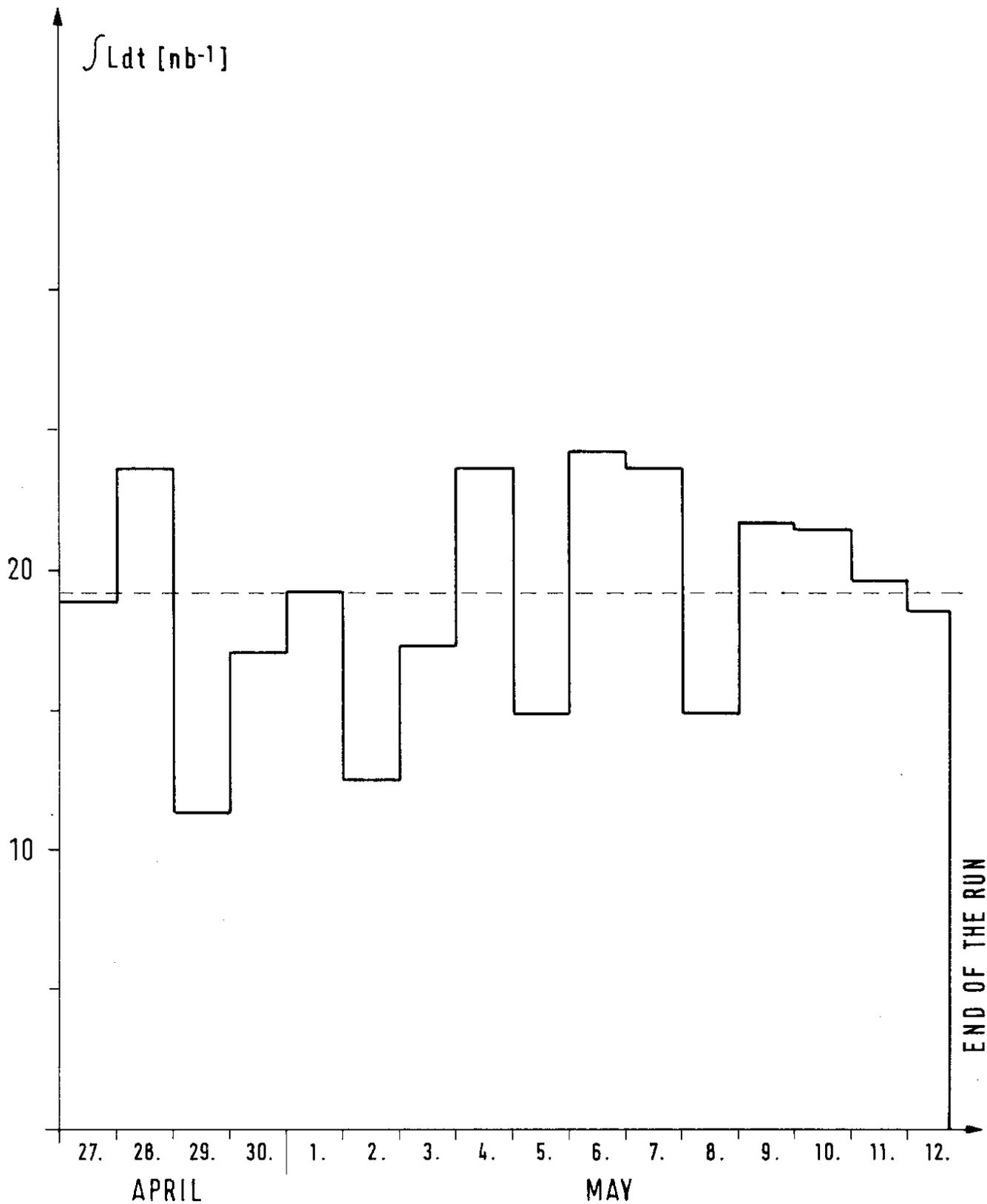$$\left[\int_{run} L \, dt = 4.7 \, nb^{-1} \,\; \hat{=} \;\; ca \; 45 \;\; \Upsilon - events \right]$$

Fig.19 Integrated Luminosity per interaction point averaged over one day

References

1. S.W. Herb et al.: Phys. Rev. Letters $\underline{39}$ (1977) 252

2. DESY Storage Ring Group: DORIS, Present Status and Future Plans, Proceedings of the IXth International Conference on High Energy Accelerator, Stanford 1974

3. G. Mülhaupt: The first Operational Experience with the Double Storage Ring DORIS, Proceedings of the IVth International Accelerator Conference, Moskau, 1974

4. H. Wiedemann: Speicherung von Elektronen und Positronen in DORIS bei DESY, Physikalische Blätter, 30. Jahrgang, Mai 1974 (Heft 5)

5. K. Wille: Betriebserfahrungen mit dem Elektron-Positron-Doppelspeicherring DORIS, Kerntechnik, 18. Jahrgang (1976) No. 1

6. DESY Storage Ring Group: DORIS - A Status Report, Proceedings of the Xth International Conference on High Energy Accelerators, July 11-17, 1977 Serpukhov b. Moskau

7. G. Mülhaupt, H. Wiedemann: Single Bunch Operation in DORIS, Interner Bericht, DESY H5-74/1 (1974)

8. H. Gerke, G. Mülhaupt: Umbau und Erweiterungsmöglichkeiten des DORIS HF-Systems für den "Einzelringbetrieb", Technische Notiz H3/76-30 DESY, May 1976

9. A. Piwinski: Proceedings of the 1977 Particle Accelerator Conference, Chicago (1977)

10. A. Piwinski, A. Wrulich: DESY-76/07 (1976)

11. A. Piwinski: DESY-77/18 (1977)

12. A. Piwinski: DESY H2-75/3 (1975)

13. H. Gerke, H.P. Scholz, M. Sommerfeld, A. Zolfaghari: Das PETRA-Cavity Internal Report DESY PET-77/08, 1977

14. H. Gerke: Überlegungen zur Regelung des HF-Systems für den Speicherring, Interner Bericht DESY H3/1 (1969)

15. A. Piwinski: Interner Bericht DESY H2-78/01 (1978)

16. R. D. Kohaupt: DESY-77/66 October 1977

17. A. W. Chao: PEP-118 April 1975

18. G. Hemmie: Post Linac Chopper, Internal Report DESY S1-74/1

19. A. Febel, G. Stange: Neues Injektionssystem für Linac II, Internal Report DESY S1-76/02

20. W. Kriens, W. Radloff: Internal Report, DESY S1-68/1

21. IEEE Transactions NS 18, 71

22. IEEE Transactions NS 22,75

23. S. Pätzold: Bunch-Trigger-Generatoren für DORIS/PETRA, Internal Report DESY H2-77/02

24. G. Barbiellini, B. Borgia, M. Conversi, R. Sontonico, Atti dell' Accademia Nazionale de Lincci, $\underline{44}$ (1968) p. 233

25. H. Kumpfert: DESY 1977- A Multi-Purpose Particle Accelerator; Proc. Int. Conf. on High Energy Acc. 1977, Protvino