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Résumé - Ce rapport d'activité traite des études sur la polarisation à DESY et plus particulièrement du dévelopement des polarimètres, des calculs de polarisation, des schemas d'optimisation, du calibrage de l'énergie des particules et des nouvelles conceptions de rotateurs de spin.

Abstract - A status report on polarization studies at DESY is presented covering polarimeter developments, calculations, optimization schemes, beam energy calibrations and new ideas for spin rotators.

INTRODUCTION

This report describes the work of the authors using the PETRA and DORIS II electron-positron storage rings. The former has a maximum energy of 23.5 GeV per beam and the latter, 5.6 GeV per beam. Clearly, experimental work with these machines is essential for preparation of polarized beam facilities on HERA /1/.

As is well known /2/, electron beams can become vertically polarized by synchrotron radiation emission up to a maximum of 92.4 % (the Sokolov-Ternov effect). However, the synchrotron radiation also excites orbit oscillations in the beam and the subsequent orbital motion in the off axis quadrupole fields causes depolarization /3,4/. The depolarizing effect is strongest when the following (intrinsic) resonance conditions are satisfied:

$$a\gamma = m \pm Q \qquad (Q = Q_x, Q_z, Q_s) \qquad \text{(linear resonance)} \tag{1a}$$

$$a\gamma = m \pm n_x Q_x \pm n_z Q_z \pm n_s Q_s \qquad \text{(nonlinear resonance)} \tag{1b}$$

where $a = (g-2)/2$, m and n are integers, g is the electron g factor and γ is the Lorentz factor. $a\gamma$ is called the spin tune.

POLARIMETER DEVELOPMENTS

The early experimental work at DESY was carried out using an argon ion laser polarimeter /5/. The principle is well known: circularly polarized laser light is scattered backwards from the oncoming electron beam and if the electrons are vertically polarized there is an up-down asymmetry in the angular distribution of backscattered photons, proportional to the electron polarization. At PETRA, the argon laser has now been replaced by a Nd-YAG laser which supplies 60 MW, 3 nsec pulses at a repetition rate of 30 Hz. The Compton scattering rate is now about a hundred times larger than previously and allows background free, high statistics measurements requiring very short measurement times to be made. Each laser pulse results in up to 10000 backscattered photons and hence in this "multiphoton mode", one measures the asymmetry in the energy flux. It is intended that this kind of polarimeter will be used at HERA.

CALCULATIONS

Until recently the only practical analytical way to calculate the polarization of arbitrary storage ring configurations has been to use the computer program SLIM /3/. This program employs a linear transfer matrix technique to describe the coupling of spin motion to orbital motion and can thus predict the strength of linear resonances. In practice however, there are several sources of non-linearity present such as sextupoles, chromatic effects and beam-beam interactions. These effects are now calculated at DESY using the tracking program SITROS by J. Kewisch /6/. SITROS predicts the same general polarization behaviour as SLIM but in addition predicts non-linear resonance behaviour (see Fig. 1). SITROS will now be used to predict beam-beam depolarization effects for HERA.

OPTIMIZATION SCHEMES

At the last conference /7/, a method of polarization optimization was described in which the depolarizing effects of arbitrary small vertical closed orbit distortions could be corrected in a controlled way with the aid of sets of eight symmetrically arranged vertical correction coils /8/. This idea has now been extended to the case where gradient errors in quadrupoles break the optical symmetry so that vertical intrinsic depolarizing resonances can appear at energies where m (Eqn. 1a) is not a multiple of the machine superperiodicity, which for PETRA is four. The depolarizing effect due to vertical oscillations receives 4 contributions proportional to the integrals /9/

$$\oint_{\mathrm{ring}} k(s) \begin{matrix}\sin\varphi_s\\ \cos\varphi_s\end{matrix} \sqrt{\beta_z} \begin{matrix}\sin\varphi_z\\ \cos\varphi_z\end{matrix} ds$$

where k(s) is the quadrupole focusing strength, φ_s is the spin phase, β_z is the vertical betafunction and φ_z is the vertical betatron phase.
When the resonance condition, $a\gamma = m \pm Q_z$, is satisfied, the depolarizing effect can then be written as a linear combination proportional to the four terms a_1-a_4

$$\begin{matrix}a_1\\ a_2\end{matrix} = \oint \begin{matrix}\sin(m\alpha)\\ \cos(m\alpha)\end{matrix} \left[\cos\varphi_z\cos(Q_z\alpha) + \sin\varphi_z\sin(Q_z\alpha)\right]\sqrt{\beta_z}\,k(s)\,ds$$

$$\begin{matrix}a_3\\ a_4\end{matrix} = \oint \begin{matrix}\sin(m\alpha)\\ \cos(m\alpha)\end{matrix} \left[\cos\varphi_z\sin(Q_z\alpha) - \sin\varphi_z\cos(Q_z\alpha)\right]\sqrt{\beta_z}\,k(s)\,ds$$

where $\alpha = \varphi_s/a\gamma$ and $0 \leqq \alpha \leqq 2\pi$. Non-zero values for a_1-a_4 for both the $a\gamma = m+Q$ and $a\gamma = m-Q$ cases can be generated independently by making small adjustments to the gradients of a set of eight symmetrically arranged quadrupoles. In a real machine where the gradient errors are unknown the Q_z resonances could then be weakened by very small empirical adjustments of the chosen quadrupoles using the calculated relationships between the coefficients a_1-a_4 and the gradient perturbations. This is in the same spirit as the previously described method of vertical closed orbit adjustments. Figure 2 shows the result of a simulation using the SLIM program for a PETRA luminosity optics with gradient and vertical closed orbit errors. Clearly, the application of both the closed orbit and quadrupole correction leads to a large improvement in the polarization. It is intended that the quadrupole scheme will be tested experimentally at PETRA.

Υ' MASS MEASUREMENT

Vertical polarization is particularly easy to obtain at the DORIS II storage ring since at this low energy (5 GeV) the depolarizing effects, which increase with energy are comparatively weak /9/. Furthermore, the small polarization build up time of just a few minutes makes DORIS very suitable for polarization studies. These features have been exploited in the use of a depolarizer to make a precise calibration of the beam energies so that a very accurate measurement of the Υ' mass could be obtained /10/. The depolarizer consists of a very weak (≈ 0.1 Gauss.m.) radial oscillating magnetic field. The vertical polarization is lost when the resonance condition /7/

$$\omega_d = \omega_c \ \bar{\nu}$$

is satisfied where $\bar{\nu}$ is the fractional part of the spin tune associated with the central beam energy, ω_c is the beam circulation frequency and ω_d is the depolarizer frequency. ω_c is large (≈ 1 MHz) and ω_d can be measured very precisely so that the central beam energy can then be measured with very high accuracy. The ARGUS and Crystal Ball experiments have thus been able to measure the hadron production cross-section at precisely known beam energies and obtain M(Υ') = 10023.1 ± 0.4 MeV. The error is mainly due to experimental counting statistics and the contribution due to systematic error in the energy measurement with the depolarizer technique is estimated to be less than 100 KeV. Similar measurements have also been made at Cornell and Novosibirsk where the masses of Υ and Υ'' have also been measured /11/. Figure 3 shows a typical plot of polarimeter asymmetry versus depolarizer frequency together with the hadronic cross-section curves measured by ARGUS and Crystal Ball.

SOLENOID SPIN ROTATORS

In order to obtain longitudinal polarization in electron-positron storage rings, spin rotator systems are needed which rotate the spins from vertical to longitudinal at the entrance to the interaction regions and back to vertical again on re-entering the arc. Conventionally it is proposed that this should be achieved by using a system of vertical and horizontal bend magnets such as in the "Mini-Rotator" of Buon and Steffen /12/.

Recently the authors of this report have developed an alternative approach based on the combined use of high field superconducting solenoids and horizontal bends /13/. The principle is illustrated in Figure 4. Vertical spins entering from the arc are rotated through 90° into the horizontal by a solenoid and a horizontal bend magnet then rotates the spins through a further 90° in the horizontal plane so that they are longitudinal at the interaction point. A second dipole and solenoid system with polarities opposite to those of the first system returns the spins to the vertical in the next arc. From the BMT equation /14/ it is clear that the field integral for the solenoid must be about $a\gamma$.23 kGauss.m and that the horizontal bends must deflect the beam by 90°/$a\gamma$, i.e. 25 mrads at the design energy of 27.5 GeV. A solenoid of 20 metres length must then supply a field of 72 kGauss. Solenoids with this high field strength are now commercially available.

When a solenoid rotates the spin by 90° around the beam direction, the combined effect of the central longitudinal field and the radial end fields is to rotate the plane of orbital oscillation by about 45°/15/. The resulting coupling of horizontal and vertical motion is undesirable in a storage ring. Furthermore, just as in the case of quadrupoles mentioned above, betatron motion in the longitudinal field and in the radial end fields can cause strong depolarization effects.

Thus the simple solenoid concept has been modified by dividing each solenoid into six short sections and interleaving quadrupoles among them /16/. Since there is no field on the axis of a quadrupole the motion of the equilibrium spin axis is not modified. However by careful choice of parameters it is possible to arrange that the combined solenoid-quadrupole set-up causes no coupling, that it has a reasonable transfer matrix and that it is "horizontally spin matched" /13/ so that horizontal betatron motion no longer causes depolarization. Both the optical decoupling and spin matching are achieved by fitting the relevant elements of the thick lens 8x8 transfer matrix /3,13/ to zero. Depolarization effects due to energy (longitudinal) oscillations in the solenoids cancel since the solenoids on opposite sides of the interaction point have opposite polarities. The effects of vertical betatron oscillations can be neglected in a perfectly aligned machine since the natural beam height is zero. Figure 5 shows a sketch of such a combined solenoid-quadrupole rotator together with the key parameters. The total length in this example is 41.6 metres. Since the equilibrium spin axis is vertical in the arcs no special spin matching is needed there. In the interaction region where the equilibrium spin direction is in the horizontal plane, horizontal spin matching is achieved by using an optics for which the change of horizontal particle direction due to betatron and dispersion motion is zero /13/.

A major advantage of this scheme is that as the beam energy is varied and the rotator field strengths are varied in proportion, the equilibrium spin axis in the arcs remains vertical and no depolarizing effects due to horizontal betatron or horizontal dispersion motion can develop. Further advantages are as follows:

1) There is little degradation of the Sokolov-Ternov polarization and according to SLIM, polarizations of up to 89 % would be obtained for HERA, when four interaction regions are equipped.
2) Reversal of helicity at the interaction point involves no moving parts or change in orbit length: it is only necessary to reverse the solenoid polarity.
3) The natural beam height is zero.
4) No vertical spin matching is needed in the arcs.
5) The degree of polarization is essentially independent of beam energy.

Rotators of this kind must of course be carefully aligned and schemes are being devised to correct for the effect of orbit distortions.

SUMMARY

To summarise, since the last Conference /7/, a number of new practical techniques have been proposed or developed which should improve our ability to obtain, measure and predict electron spin polarization and to obtain longitudinal polarization.

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English translation: DESY Internal Report DESY L-Trans 286
These authors have also proposed solenoid spin rotators and have suggested that orbital decoupling be achieved by inserting quadrupoles between the two halves of each solenoid.

Figure Captions

Fig. 1a: A simulation using the program SITROS of the polarization expected at PETRA between $a\gamma = 37$ and $a\gamma = 38$ when there is an r.m.s. vertical closed orbit distortion of 1.5 mm. Both linear and nonlinear depolarizing resonances can be clearly seen.

Fig. 1b: A simulation of the PETRA polarization under the same conditions as in Fig. 1a, in this case using the SLIM program. As expected only the linear resonances are seen.

Fig. 2: A simulation of the vertical closed orbit and gradient error correction schemes in the region of 22 GeV.
Curve A) Polarization predicted by SLIM with both kinds of machine setting error present: strong depolarizing resonance effects are seen.
Curve B) Polarization prediction after application of the vertical closed orbit correction.
Curve C) Polarization after both the closed orbit and gradient corrections: the depolarizing resonances are now strongly suppressed.

Fig. 3a: Hadronic production cross-sections plotted versus C.M. energy in the region of the γ' as measured by the ARGUS and Crystal-Ball experiments.

Fig. 3b: An example of a depolarization curve: The polarimeter asymmetry is plotted as a function of depolarizer frequency. At the centre of the dip the depolarizing resonance condition is satisfied. The single beam energy scale is also indicated.

Fig. 4a: A sketch indicating how solenoids and dipoles can be combined to rotate vertical spins into the longitudinal direction. The helicity at the interaction point (I.P.) is reversed by reversing the solenoid polarity.

Fig. 4b: A sketch indicating how rotators and dipoles are combined to form a complete rotator system for one interaction region of an electron ring.

Fig. 5: The detailed layout of a solenoid quadrupole rotator which produces no overall optical coupling and is "horizontally spin matched".

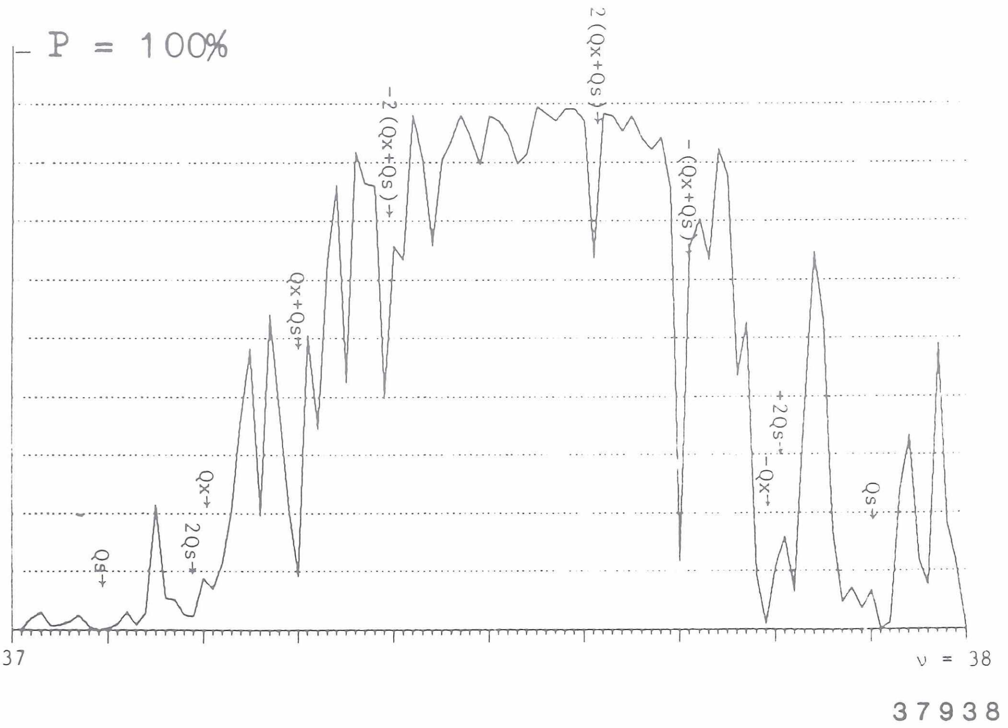

P = 100%
Qs→
2Qs→
Qx→
Qx+Qs→
-2(Qx+Qs)→
2(Qx+Qs)→
-(Qx+Qs)→
-2Qs→
-Qx→
Qs→
37
ν = 38
37938

Fig. 1a

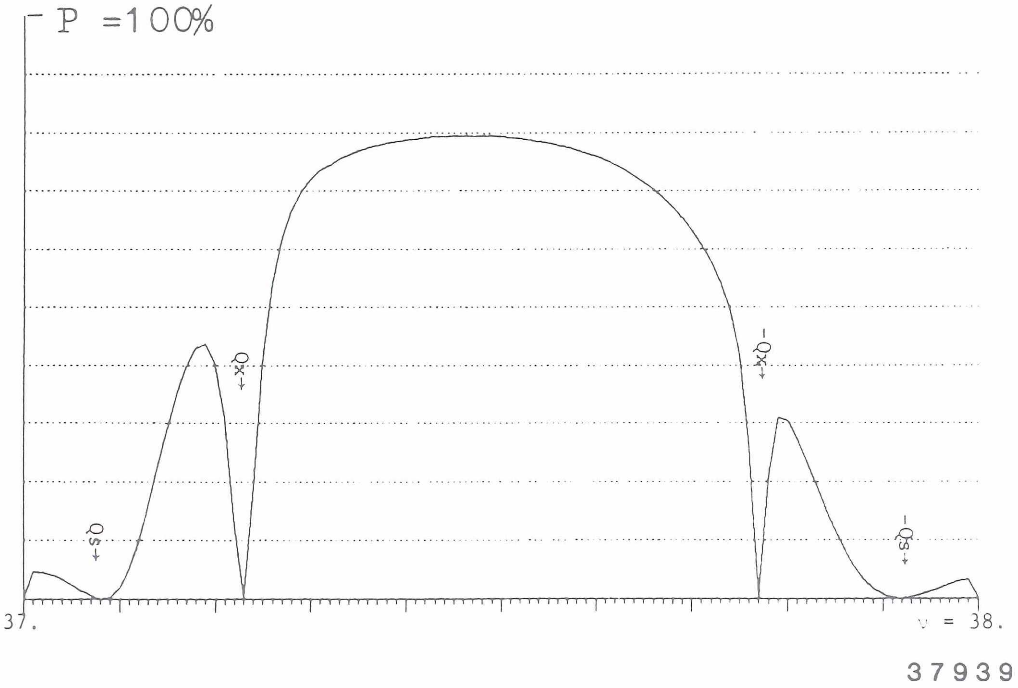

P =100%
Qs→
Qx→
-Qx→
-Qs→
37.
ν = 38.
37939

Fig. 1b

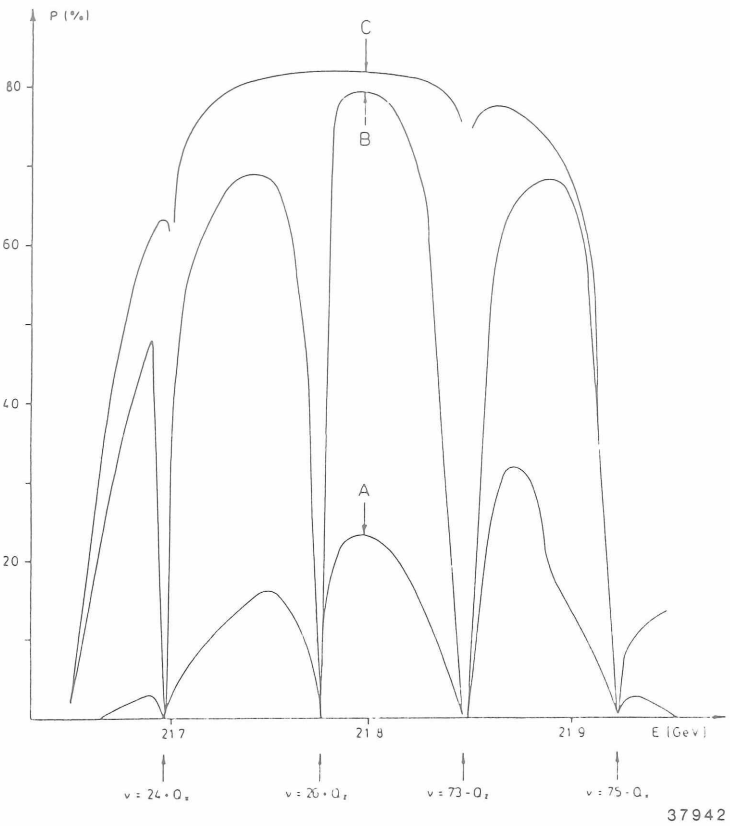

P (%)
C
B
A
80
60
40
20
21.7
21.8
21.9
E [GeV]
ν = 24 + Q_x
ν = 26 + Q_z
ν = 73 − Q_z
ν = 75 − Q_x
37942

Fig. 2

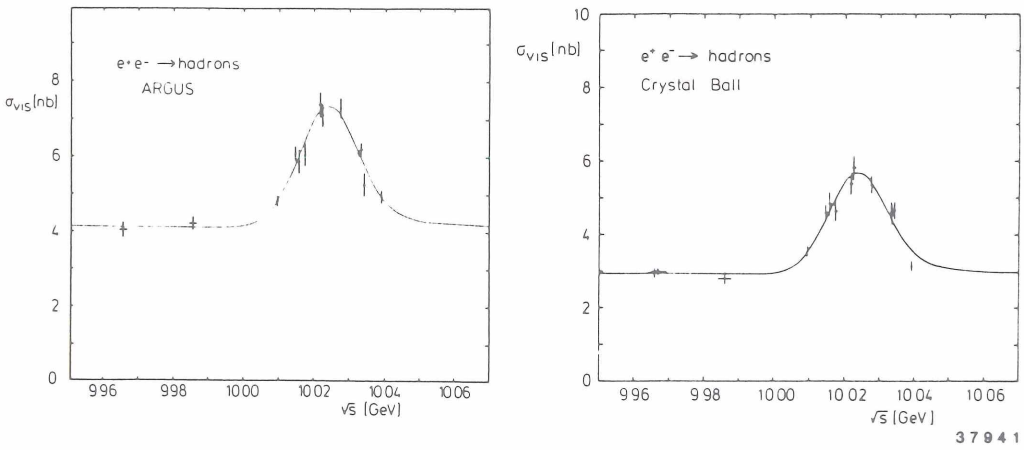

e+e- → hadrons
ARGUS
σ_vis [nb]
8
6
4
2
0
9.96
9.98
10.00
10.02
10.04
10.06
√s [GeV]
10
σ_vis [nb]
e+ e- → hadrons
Crystal Ball
8
6
4
2
0
9.96
9.98
10.00
10.02
10.04
10.06
√s [GeV]
37941

Fig. 3a

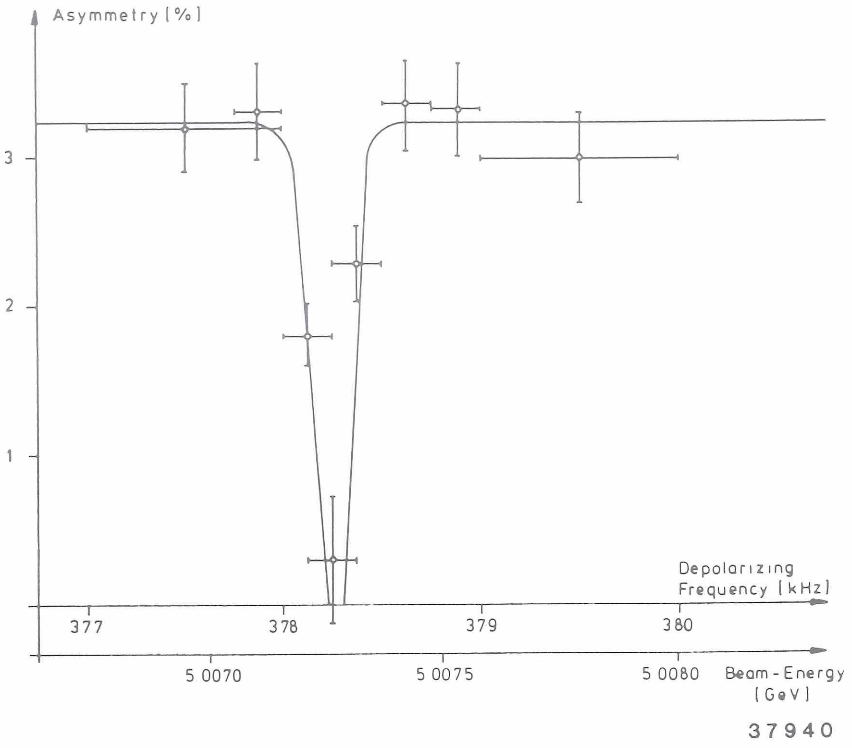

Asymmetry [%]
3
2
1
Depolarizing Frequency [kHz]
377
378
379
380
5.0070
5.0075
5.0080
Beam-Energy [GeV]
37940

Fig. 3b

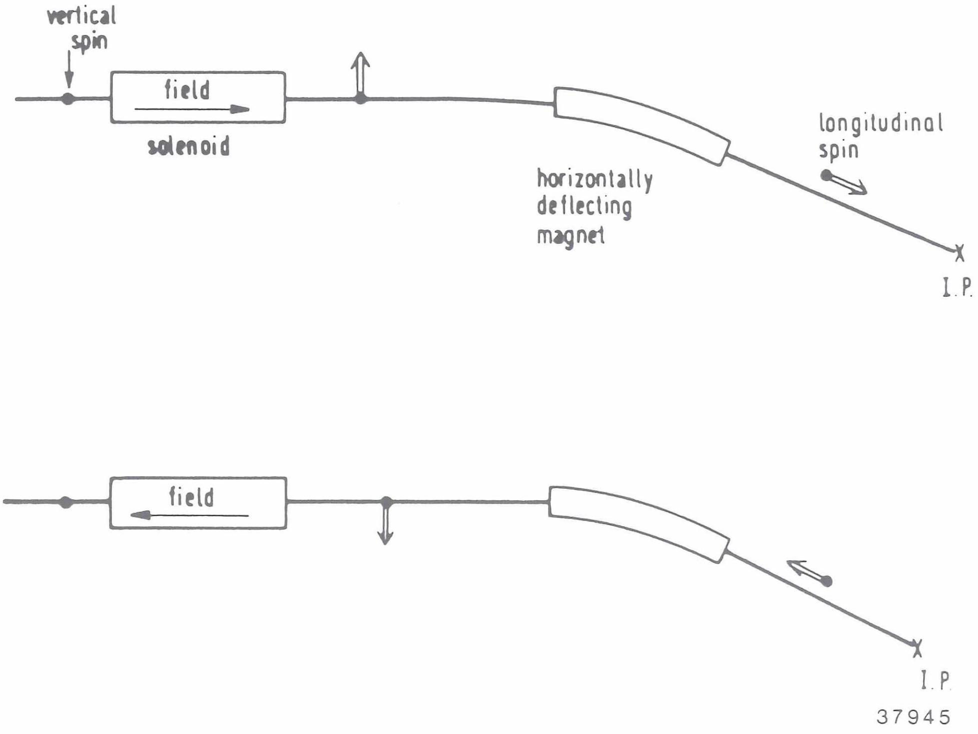

vertical spin
field
solenoid
horizontally deflecting magnet
longitudinal spin
I.P.
field
I.P.
37945

Fig. 4a

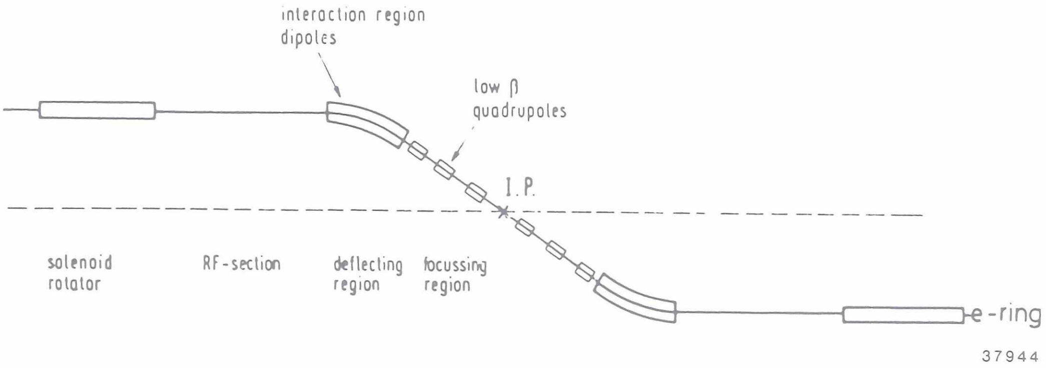
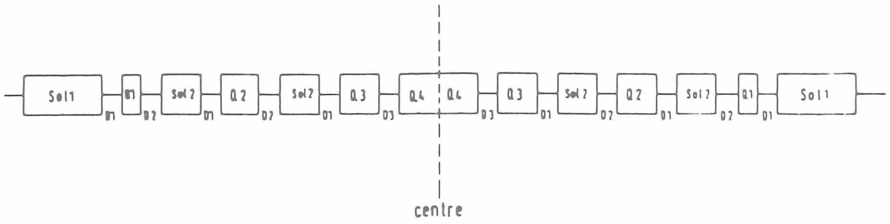


Fig. 4b



Sol 1 = Solenoid 5,0 m long 7,2 T } at 27.5 GeV
Sol 2 = Solenoid 2,5 m long 7,2 T }

Quadrupoles: Q1 = 1m long K = 0,007 m^{-2}
Q2 = 2m long K = -0,103 m^{-2}
Q3 = 2m long K = 0,124 m^{-2}
Q4 = 2m long K = -0,116 m^{-2}

Drift spaces: D1 = 40 cm
D2 = 70 cm
D3 = 120 cm

37943

Fig. 5