# Vertical and Longitudinal Electron Polarization at HERA

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*Abstract*

High transverse spin polarization is now a routine aspect of the operation of the DESY Hadron Electron Ring Anlage (HERA). In May 1994 a pair of spin rotators was brought into operation for the first time and longitudinal polarizations of over 60% were observed. This is the first time that in an electron storage ring longitudinal polarization has been obtained using spin rotators to rotate the naturally occuring transverse polarization. Results are presented here together with a short description of the HERA spin rotator concept and related problems.

## 1 INTRODUCTION

Longitudinal polarization of the electron beam can be of great interest for both the experiments, H1 and ZEUS, already installed at the HERA collider. The experiment HERMES will use the longitudinally polarized electron beam against a polarized gas target to study the spin structure functions of the proton and neutron.

The spin of an electron moving in a homogeneous and constant magnetic field can flip from parallel to antiparallel, and viceversa, with respect to the field direction by photon emission (Sokolov-Ternov (S.T.) effect [1]). The two transitions have different probabilities so a maximum polarization of 92.4 % is reached at equilibrium. In this way electrons in a planar storage ring can become polarized anti-parallel to the direction of the field in the guiding dipoles (where radiation mainly takes place), i.e. in the vertical direction.

To understand how the spins of a S.T. polarized electron beam can be tilted into the horizontal plane, we recall that the expectation value of the spin vector operator of a non radiating particle in a EM field moves according to the Thomas-BMT equation [2, 3]

$$\frac{d}{ds}\vec{S} = \vec{S} \times \vec{\Omega}$$

where (MKS)

$$\vec{\Omega} = \frac{e}{m_0 \beta c}\Big[\Big(a+\frac{1}{\gamma}\Big)\vec{B} - \frac{a\gamma}{\gamma+1}\vec{\beta}\cdot\vec{B}\vec{\beta} - \Big(a+\frac{1}{\gamma+1}\Big)\vec{\beta}\times\frac{\vec{E}}{c}\Big]$$

The spin tune $\nu$, defined as the number of spin precessions per revolution, is given, in a flat machine, by $a\gamma$ (for electrons $a \simeq .00116$).

It is clear that at high energy only magnetic fields perpendicular to the motion direction act in an efficient way on the spin direction and that to bring the spin along the particle motion at an interaction point one must introduce a special insertion involving vertical bending magnets. This means that the geometry of the ring will no longer be planar.

Clearly, to restore the vertical direction of the spin at the entrance of the arc a second rotator is needed.

## 2 THE HERA MINI-ROTATOR

Various kinds of rotators were studied for HERA. The scheme finally adopted – the so called Mini-Rotator [4] – consists of a sequence of vertical and horizontal bending magnets which moves the spin from the transverse to the longitudinal direction as shown in Figure 1 for 27.519 GeV. The HERA Mini Rotator scheme is space saving, offers the possibility of reversing the spin helicity at the IP and can work on a large range of energy (from 27 up to 35 GeV). The four vertical magnets of each rotator form a 21 cm (at 27.519 GeV) high closed vertical bump; the two vertical bumps are antisymmetric with respect to the IP. The horizontal magnets BA, BC and BD form a horizontal bump (the BB's contribute to the closure of the ring); the two horizontal bumps are symmetric. As the spin precession angle is $a\gamma$ times the orbit angle, the reference orbit must change when energy is varied. The spin helicity is changed by reversing the sign of the vertical bending magnets; for this reason at the rotator location the beam pipe is provided with special bellows and is mounted on remotely controlled jacks which allow to adapt the vertical shape of the rotator to energy and helicity. There are no quadrupoles in between the vertical bending magnets and the rotator does not contribute vertical dispersion to the rest of the machine.

## 3 DEPOLARIZING EFFECTS AND CORRECTION SCHEMES

### 3.1 Spin diffusion mechanisms

Stochastic photon emission excites both betatron and synchrotron motion so that in a real ring, made not purely of dipole magnets, the particles experience stochastic fields in the quadrupoles (mainly). In a perfect planar machine, neglecting recoil effects, the motion is confined to the horizontal plane and there is no diffusion as the spins lie along the field direction, namely vertical.

In the presence of horizontal magnetic fields however (spin rotators and/or distorted closed orbit) the nominal spin direction, $\hat{n}_0$[11], is not anymore in the vertical direc-

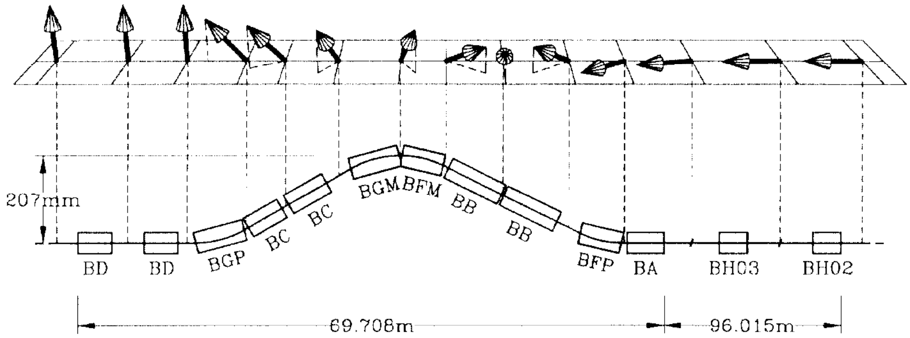


Figure 1: Mini rotator scheme (side view) and spin transformation

tion and the particle motion is not confined to the horizontal plane. As a consequence the spins of the individual particles will precess both around the horizontal and the vertical fields when going off axis through the quadrupoles, diffusing away from $\hat{n}_0$. Through the same mechanisms, energy oscillations lead to spin diffusion too. Diffusion, i.e. depolarization, is strongest when the resonance conditions

$$\nu \pm mQ_x \pm nQ_z \pm pQ_s = integer$$

are approached.

### 3.2 *Depolarization due to the rotator*

The presence of strong horizontal magnets with a field in the direction opposite to the main guiding field results in lowering the S.T. equilibrium polarization to 90.8 %, even with vertical bending magnets off. But much more serious are the consequences of turning on the vertical bending magnets. In this case $\hat{n}_0$ between the rotator pair is in the horizontal plane so that the spins of particles moving off axis through the quadrupoles between the rotators will diffuse strongly away from the nominal direction. Moreover, as vertical betatron motion is also excited, diffusion takes place also all along the rest of the ring.

So, even before considering alignement errors, the polarization level achievable in a ring with rotators can be much lower then 92.4%. The cure consists in adjusting the optic, namely the quadrupole strengths, in order to minimize the above mentioned effects ("spin matching" [6, 4]) For the actual HERA-e design the spin-matching conditions are:

$$\tan[\mu_x(s_R) - \mu_x(IP)] = -\alpha_x(s_R) \tag{1}$$

$$\int_{IP}^{s_R} ds\, \hat{n}_0 \cdot \hat{s}\, K\sqrt{\beta_z}\cos\mu_z = 0 \tag{2}$$

$$\int_{ARCS} ds\, e^{i(\psi\pm\mu_z)} K\sqrt{\beta_z} = 0 \tag{3}$$

$$\int_{IP}^{s_R} D_x K = 0 \tag{4}$$

where $s_R$ denotes the rotator entrance, $\psi$ is $\nu$ times the cumulative bending angle, $\hat{s}$ is the unit vector along the motion direction and $K$ is the quadrupole strength.

It is worth noting that only the condition 3 is energy dependent, the other conditions are purely optical. The thick, solid line in Figure 2 shows polarization vs energy for the actual HERA-e optic with one rotator pair around the IP East (SLIM[7], linear calculation, ideal machine) after spin matching at 27.519 GeV. The other graphs correspond to the polarization related to the three degrees of freedom of the motion separately.

The spin matching condition 3 is well fulfilled at 27.98 GeV too, which results to weaker resonances and higher polarization around both of these two energy values. Condition 4 could not be fulfilled exactly and is limiting the maximum level of polarization, which is 84 %.

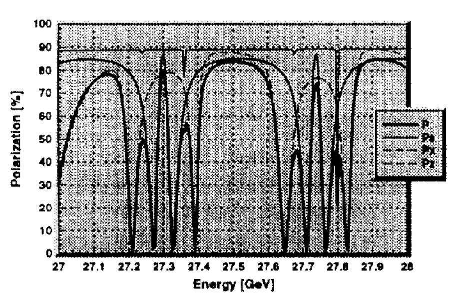


Figure 2: Spin matched undistorted optic (SLIM)

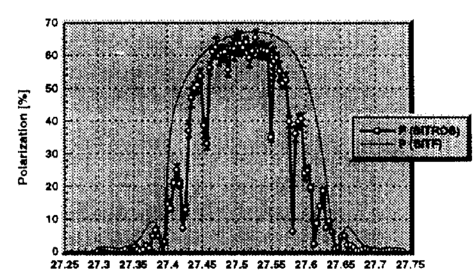


Figure 3: Spin matched optic in presence of errors and corrections (SITROS)

### 3.3 *Depolarization due to random errors*

In addition one must take into account the presence of random errors which, as briefly explained in 3.1, can lead to spin diffusion even in a planar machine. The most dangerous is the vertical displacement of the quadrupoles which generates vertical spurious dispersion and a tilt of the spin from $\hat{n}_0$. Simulations and experience show that in HERA-e the first is reduced to acceptable values by the usual closed orbit correction. The second needs special care. The rms value of the tilt depends on the energy and on the optic. After normal closed orbit correction it is typically around 30 mrad, which is enough to limit the polarization to no more than 10-20 % and must be corrected. The correction scheme used originally at PETRA [5] has been generalized to a machine including vertical bending magnets and other "exotic" magnets [8]. The most important harmonics of a "spin-orbit" function are minimized by using 8 vertical closed bumps. Typically the tilt of the spin is reduced to less then 15 mrad and one expects a maximum polarization of about 60-70 %. As an example in Figure 3 the result of a non linear calculation with the tracking code SITROS[9, 10] is shown for the actual HERA-e optic with one rotator pair in the East, in the presence of random distortions and after correction. The correction method as been successfully applied in 1993 to improve the transverse polarization at HERA-e[11] and in May of this year, after the introduction of the spin rotator insertion in East (see later).

It is worth noting that the PETRA scheme (or those similar used at LEP and TRISTAN) would not give for HERA-e, in presence of rotators, a satisfactory correction. This is for HERA-e due not to the (small) contribution of the horizontal closed orbit between the rotator pair, but mainly to the presence of the horizontal bending magnets in the rotators.

## 4 MEASUREMENTS

Similarly to last year the betatron tunes $Q_x = 47.1$ and $Q_z = 47.2$ were chosen in order to push the first order resonances $\nu \pm Q_{x,z}$ towards integer spin tunes. The synchrotron tune varied between 0.055 and 0.060. $\beta$-beating was measured to be around 10%, compatible with expectations. The electron polarization was measured by using the Compton polarimeter in the West[11], where $\hat{n}_0$ is vertical. With rotators off the machine energy was set to 27.54 GeV i.e. half way between the two integers $\nu = 62$ and $\nu = 63$. By using the harmonic bumps transverse polarization (vertical bending magnets off) between 65 and 75 % (asymptotic) was observed in several runs. Then the beam was dumped and the rotators brought into operation. New beam was injected and ramped to 27.52 GeV corresponding, with rotators on, to $\nu = 62.5$. The polarization grew up to around 57 % (asymptotic) without further optimizations (see Figure 4). This is consistent with the idea that the polarization is limited by the tilt of the spin due to random errors and that this tilt was already well compensated before switching the vertical bending magnets on. After a further small energy adjustment the asymptotic longitudinal polarization grew to between 61 and 78 % during successive runs. These values, consistent with SITROS forecasts, are well above the minimum required for the HERMES experiment.

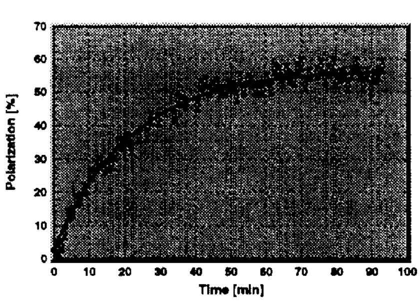


Figure 4: Measured longitudinal polarization vs time; the asymptotic value is 57%

## 5 CONCLUSIONS AND OUTLOOKS

Longitudinal polarization has been observed for the first time in a high energy electron storage ring and high values obtained. The observations were made with a spin matched optic and with experiment magnets on, but without collisions. Last year there was no evidence of depolarization due to the collisions with the proton beam. HERMES data taking will start next year; two pairs of rotators for H1 and ZEUS have been ordered.

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