Polarisation 2001

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1 SUMMARY

We give an overview of the impact of the Hera luminosity upgrade on the polarisation operation.

2 INTRODUCTION

Following the suggestions of the experimental and theoretical physics communities an increase of the HERA luminosity has been studied in the last few years and is currently being realised. The aim is to improve the collider luminosity by about a factor 4.7 without spoiling the polarisation for HERMES. Longitudinal $e^{\pm}$ polarisation for the collider experiments was one of the issues of the original HERA design. Therefore the two rotator pairs for H1 and ZEUS, ready since 1997, are now going to be installed.

The solution adopted has been described in several papers (see for example [1],[2],[3]). We recall here only the aspects which have a direct impact on polarisation operation, namely:

- New Interaction Region designs (no more mirror symmetry around IP's) with stronger quadrupoles.
- Anti-solenoid removal (due to lack of space).
- Larger focusing in the FODO cells in order to reduce the $e^{\pm}$ horizontal emittance, ϵ_x.
- RF frequency shift (to get a further ϵ_x reduction).

3 UNCOMPENSATED EXPERIMENT SOLENOIDS

3.1 Effects of experiment solenoids

The experiment solenoids introduce

- Coupling between the radial and vertical motion
- Distortion of the polarisation axis $\hat{n}_0(s)$ (the periodic solution to the Thomas-BMT equation on the closed orbit).

In the old design these effects have been perfectly compensated by using anti-solenoids[4]. In the new design the betatron coupling will be corrected by 4 independently powered skew quadrupoles per IP.

According to the Thomas-BMT equation, the spin of a charged particle moving in a magnetic field performs a precession around the vector $\vec{\Omega}$

$$\vec{\Omega} = -\frac{e}{m_0}\left[\left(a+\frac{1}{\gamma}\right)\vec{B} - \frac{a\gamma}{\gamma+1}\vec{\beta}\cdot\vec{B}\vec{\beta}\right]$$

(MKS) with $a \equiv (g-2)/2 \simeq 0.00116$.

For a $e^{\pm}$ moving in a field B_{sol}, parallel to its velocity, the precession angle, θ, is given by

$$\theta = -\frac{e}{p}(1+a)B_{sol}L$$

For example, at 27.5 GeV the H1 solenoid, with B_{sol}=1.1 T and L=7.3 m, would tilt an initially vertical spin by about 86 mrad. Under such conditions the radiative polarisation (Sokolov-Ternov effect) would be overwhelmed by depolarisation[5].

However, by installing the already prepared two pairs of spin rotators around the IP's North and South, the $\hat{n}_0(s)$ will be longitudinal at the experiment solenoids and will therefore not be perturbed by them (except for the effects described in section 3.3).

3.2 Polarisation for an optics with 3 rotator pairs

Nevertheless, with the nominal spin direction parallel to the solenoid field, we must still expect some reduction of the achievable polarisation.

The presence of two additional spin rotators reduces the Sokolov-Ternov polarisation level and introduces additional spin diffusion, to be cured, at linear level and on one turn, by "spin matching" the optics.

The effects of the solenoids themselves are described in[6].

Due to the relatively large particle energy, the experiment solenoids have been treated as a perturbation and ignored when designing the new optics. However, subsequent local spin matching of the optics in the presence of the solenoids turned out not to be possible. A mutual compensation of the two solenoids is not feasible either, mainly because it would require the phase advance between the two IP's to be a multiple of π.

Due to the non-symmetric IR, the whole section between the rotator pair must be considered when designing the optics. Including the spin matching conditions, we must deal with 17 conditions, instead of 9, and this makes the design quite tedious. For the latest IR design version, it turned out that all quadrupoles left and right of the IP up to the rotator had to be powered independently requiring 14 extra power supplies. It is likely that, in the starting phase, only 7 of them will be available.

The spin matched optics is designed by using the code SPINOR[7].

Fig. 1 shows polarisation versus energy for the ideal optics with 3 pairs of rotators and without solenoids. The polarisation is computed by using the code SLIM[8] (linear spin motion); the three dashed lines correspond to the polarisation related to each of the three degrees of freedom of the motion.

To stress the fact that a solenoid may be not completely harmless even when $\hat{n}_0 \parallel B_{sol}$, we introduced a H1 "equivalent" solenoid, 3.9 m long with a field of 2.0 T, around the

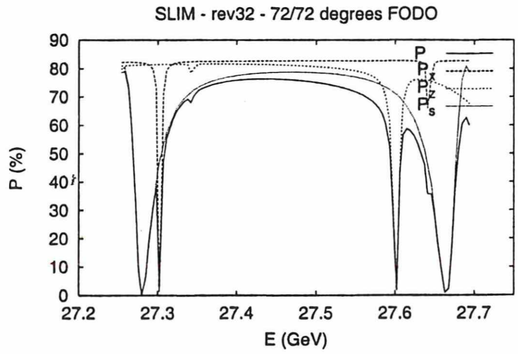

Figure 1: Polarisation vs. energy for the ideal upgraded HERA optics in the presence of 3 rotator pairs. The dashed lines refer to the polarisation related to the individual degrees of freedom of the motion.

IP North; the betatron coupling is compensated by 4 skew quadrupoles. Comparing Fig. 2 with Fig. 1 one observes a polarisation reduction, mainly related to the horizontal betatron motion, as expected from the effects described in[6].

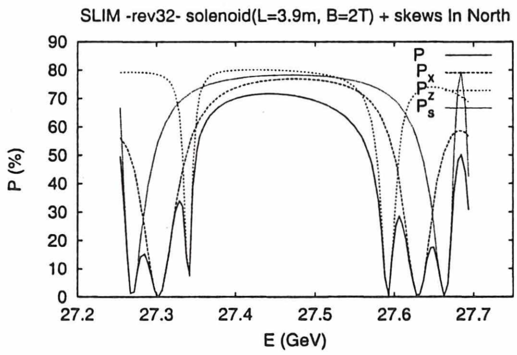

Figure 2: Polarisation vs. energy for the ideal upgraded HERA optics in the presence of three rotator pairs. A solenoid with an integrated strength of 7.8 Tm has been introduced around the IP North.

3.3 *Distortions due to the H1 solenoid*

While the Zeus solenoid ($B_{sol}L$=4.4 T m) fits physically into the 3.9 m free space between the machine magnets, the H1 solenoid ($B_{sol}L$=7.6-8.3 T m, L=7.3 m) overlaps with the machine magnets, namely with the long combined function superconducting magnet GO. Moreover it is longitudinally shifted by 1.1 m. Therefore the nominal particle velocity and $\hat{n}_0$ are not perfectly parallel to the solenoid field. The overlap produces a (mainly vertical) orbit distortion and the longitudinal offset produces a $\hat{n}_0$ distortion.

The trajectory distortion due to the H1 solenoid was computed initially by solving the equation of particle motion for the transverse coordinates and the Thomas-BMT equation in a general 3-dimensional field. Later on, symplectic (linear) maps produced by numerical integration of the particle/spin motion in the measured fields were introduced in the existing codes SLIM, SLICK[9] and SITF/SITROS[10],[11],[12]. In parallel we also used interleaved slices of combined function magnets, solenoids and vertical correctors ("sandwich" model). This approach doesn't need code changes, but of course leads to unphysical non-canceling solenoid end fields. If one is not interested in orbit and radiation effects (for example for the betatron coupling correction) this problem can be overcome by using interleaved thin lens pure quadrupoles and solenoids[13].

The trajectory distortion through the H1 solenoid is shown in Fig. 3.

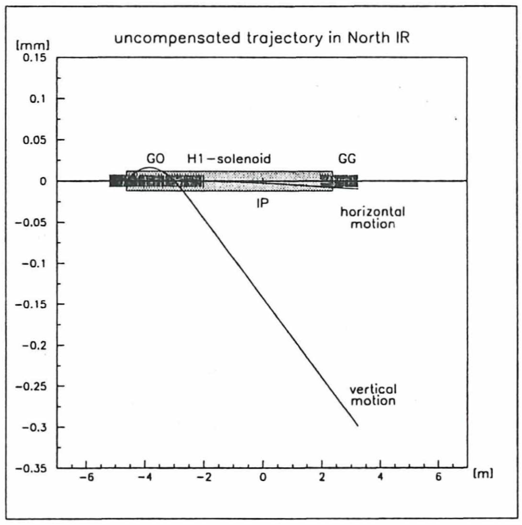

Figure 3: Trajectory distortion through the H1 solenoid.

Table 1 lists the components, at the entrance and at the exit of the H1 solenoid, of a spin, initially vertical along the arc upstream of the IP North.

Table 1: Spin components through H1 solenoid

	entrance	exit (nominal)	exit
s_x	-0.490	0.490	0.490
s_l	0.872	0.872	0.871
s_z	0.000	0.000	-0.006

The orbit will be locally compensated by using the GO and GG vertical dipole windings.

The $\hat{n}_0$ distortion will be quasi-locally compensated by non-symmetric settings of the vertical bending magnets in the rotators left and right of the IP North. This will be done by exploiting the already existing extra vertical correction coils of the vertical bends. For a change of the helicity, the magnitudes as well as the signs must be changed.

3.4 *Polarisation in the presence of the solenoids*

Fig. 4 shows the polarisation for the optics with 3 rotator pairs when the H1 solenoid is turned on. The rms vertical orbit shift is 1.2 mm and the rms tilt of $\hat{n}_0$ is 8.8 mrad (due to the solenoid and to the uncorrected orbit); the ratio of the vertical emittance to the horizontal one is 6.9 % (nominal: 2.4 %).

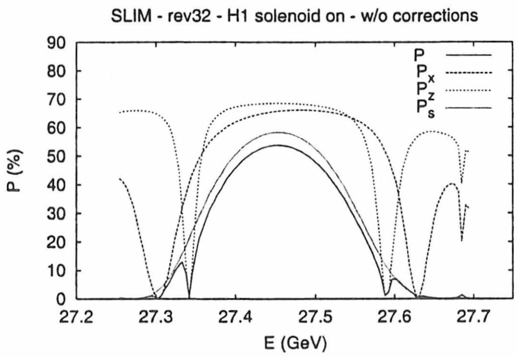

Figure 4: Polarisation vs. energy with H1 solenoid on, no corrections.

Although these distortions are quite small in comparison with those caused by random errors the impact on the polarisation is large. The results shown are obtained by using SLIM with the sandwich model.

Fig. 5 shows the polarisation after the orbit, the coupling and $\hat{n}_0$ have been corrected as described in the previous section.

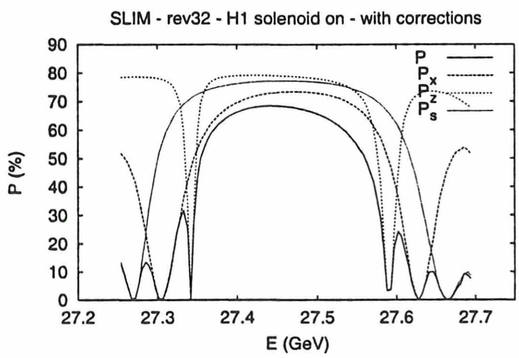

Figure 5: Polarisation vs. energy with H1 solenoid and corrections.

Comparison with Fig. 2 shows that there is no margin for further improvements.

3.5 *Comparison between models*

The numerical maps for the H1 solenoid have been computed by using the measured field data along the magnet axis. Three different reasonable shapes of the field fall off have been considered[14]. The differences for the particle and spin trajectories are negligible. Moreover a fine tuning of the orbit can be always easily done empirically.

Concerning orbit and polarisation there is also a reasonable agreement between the map approach and the sandwich model, even when the number of slices is kept small for simplicity.

As an example, we show the SITF polarisation results obtained for the sandwich model (see Fig. 6) and by using the numerical symplectic maps instead (see Fig. 7).

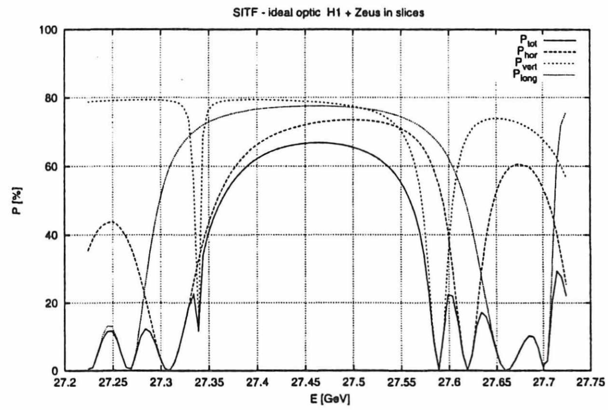

Figure 6: Polarisation vs. energy for the ideal optics with 3 rotator pairs and with H1 and Zeus solenoids on; sandwich model.

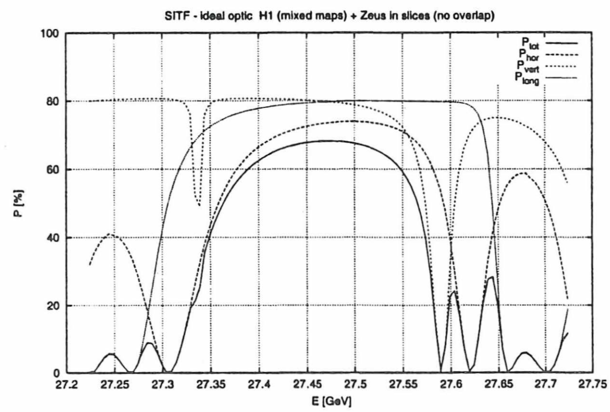

Figure 7: Polarisation vs. energy for the ideal optics with 3 rotator pairs and with H1 and Zeus solenoids on, by using the H1 numerical maps.

The coupling has been corrected by minimising the off-diagonal matrix elements by a 4 parameter minimisation algorithm. In Table 2 are listed the skew quadrupole strengths for the H1 solenoid compensation.

There are some differences between the results for the different models. They are small, but an empirical fine tuning is almost impossible unless one has orthogonal knobs.

Table 2: Skew quadrupole strengths (m^{-2})

	maps A1	maps A2	maps B	sandwich crude	sandwich thin quads
Q1	-0.0031	-0.0036	-0.0036	-0.0034	-0.0033
Q2	0.0005	-0.0013	-0.0012	0.0013	-0.0004
Q3	-0.0091	-0.0105	-0.0105	-0.0097	-0.0097
Q4	0.0022	0.0022	0.0022	0.0025	0.0022

4 NON-LINEAR POLARISATION CALCULATION

The code SITF/SITROS presented some problems, namely:
• In our version of the program, the treatment of solenoids was not correct in the presence of rotators.
• Radiation simulation at 32 points turned out to be no longer adequate, resulting in too large equilibrium emittances. The radiation has been therefore extended to all dipoles: results are better, but the code became of course much slower.
• To avoid problems with the consequent small spin phase advance between radiation points, the tracking of the spins was replaced by quaternion tracking.

Fig. 8 shows the polarisation results with the non-linear spin motion calculation of SITROS.

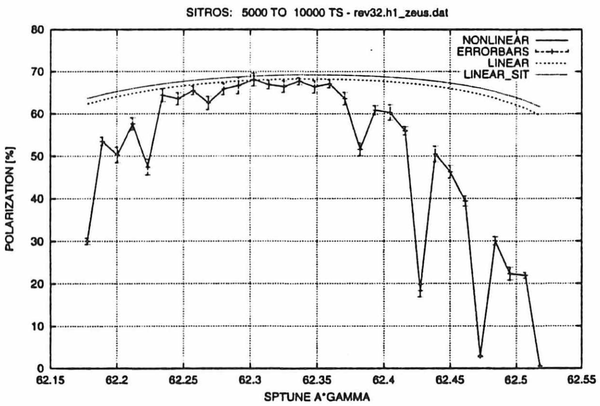

Figure 8: Polarisation vs. $a\gamma$ for the ideal optics with 3 rotator pairs and with H1 and Zeus solenoids on, by using the numerical maps for the H1 solenoid. Linear and non-linear calculation.

5 EFFECTS OF RANDOM DISTORTIONS

Unavoidable random alignment errors can cause a tilt of $\hat{n}_0(s)$ and consequent strong depolarisation[5]. We have considered the e^- optics with 3 rotator pairs and, initially, without experiment solenoids. The assumed rms value of the quadrupole horizontal and vertical displacement is 0.3 mm with a 3 σ cut. In some cases a roll-angle error (0.35 mrad rms value) has also been introduced. No beam position monitor displacements and no field errors have been considered.

Table 3: Expected $\delta\hat{n}_0$ and P after orbit correction

$\delta\hat{n}_0$(mrad)	$P(\%)$	$P_x(\%)$ $P_z(\%)$ $P_s(\%)$
35.6±11.1	12.3±11.8	73.5±4.1 72.5±4.4 11.3±11.9

Table 4: Expected $\delta\hat{n}_0$ and P with additional harmonic bumps optimisation

$\delta\hat{n}_0$ (mrad)	$P(\%)$	$P_x(\%)$ $P_z(\%)$ $P_s(\%)$
16.9±3.7	67.5±4.8	71.5±4.1 70.8±5.3 67.6±5.8

Since the differences in the orbit and polarisation results between the symplectic map approach and the "sandwich" model were not large, we decided to keep PETROS[15] (the code we use for simulating the effects of random errors) unchanged also when turning on the solenoids.

In Table 3 the expected $\delta\hat{n}_0$ and polarisation are quoted; the values are averaged over 6 seeds. The orbit has been corrected down to x_{rms}=0.76±0.06 mm and z_{rms}=0.81±0.14 mm.

The polarisation for the same 6 distorted optics has subsequently been optimised by using the "harmonic bumps". Results are quoted in Table 4.

In summary:
• The closed orbit must be corrected down to $\simeq$ 0.7 mm to ensure P above 60% (after harmonic bump optimisation).
• In comparison with the old optics, there is larger $\hat{n}_0$ perturbation, as expected. Probably all 8 harmonic components must be corrected.
• After $\delta\hat{n}_0$ correction the polarisation levels for the 3 degrees of freedom are similar.

We have also noticed that in some cases the polarisation is limited by the large horizontal dispersion around the IP's North and South. Therefore it is sensible for the future to have a dispersion correction algorithm; a dispersion correction via MICADO has been already implemented in PETROS.

In September, at the time of this meeting, we have got the first SITF/SITROS results in the presence of random errors and with H1 and Zeus solenoids turned on. In some cases it was quite difficult to correct the $\hat{n}_0$ tilt and unpleasant gymnastics involving tuning the rotator bending magnets was needed to get decent polarisation. It turned out that our optimisation simulation algorithm had to be improved. Af-

Table 5: Beam-beam tune shift

	current	lumi upgrade
$\Delta\nu^e_x$/IP	0.013	0.027
$\Delta\nu^e_z$/IP	0.033	0.041

terwards, it was possible to correct also the "difficult seeds" and get reasonable polarisation in the usual way.

6 BEAM-BEAM EFFECTS

An important source of depolarisation in a collider like Hera is the interaction with the counter-rotating proton beam. The strength of this interaction is usually parametrised by the so called incoherent tune shift, $\Delta\nu$, given by

$$\Delta\nu^{e,p}_{x,z} = \frac{r_{e,p}}{2\pi\gamma_{e,p}} \frac{N_{p,e}\beta^{e,p}_{x,z}}{(\sigma^{p,e}_x + \sigma^{p,e}_z)\sigma^{p,e}_{x,z}}$$

The lepton incoherent tune shifts for the old optics and for the luminosity upgrade optics are quoted in Table 5 for I_p=100 mA and $\epsilon^p_x = \epsilon^p_z$=18 mm mrad (2-$\sigma$ normalised emittance).

The impact on polarisation of the beam-beam force has been clearly observed in practice (see for example[16]). In comparison with observation, the limitations foreseen by SITROS[17] seem too severe. We are starting to look into this topic.

7 RECENT POLARISATION STUDIES

Polarisation operation after the luminosity upgrade is expected to be more difficult than in the past years. At the end of August, before shutting down the machine, a part of the machine studies was dedicated to exploring some of the issues. G.Hoffstätter[18] has reported on the machine studies program. We shall just comment that the results of the polarisation studies look encouraging. In particular the effect of the RF shift is not as large as predicted by the non-linear calculations.

8 MACHINE COMMISSIONING FOR POLARISATION

The commissioning of the machine for polarisation after the shut down will be more difficult than in the past due to the presence of two more rotators and of the uncompensated solenoids. It is best to attack one problem at a time and to have the possibility of some empirical fine tuning.

Two things must been kept in mind: 1) there is no polarisation with one of the experiment solenoids turned on without having a nominal longitudinal $\hat{n}_0$ at the solenoid location; 2) the optics is spin matched only when all three rotator pairs are on simultaneously.

A possible scenario could be:

- Demonstrate reduction of coupling generated by each of the experiment solenoids by using the skew quadrupoles.
- Establish polarisation with rotators and solenoids off.
- Turn (all) rotators on and retune the machine (orbit+harmonic bumps, energy...).
- Turn on solenoids and skew quadrupoles one after the other; if necessary correct orbit and reoptimise harmonic bumps, in addition to the local correction of orbit and $\hat{n}_0$ for the H1 solenoid.

9 SUMMARY AND OUTLOOK

- The luminosity upgrade will have a large impact on HERA-e and on polarisation.
- The orbit must be very well corrected.
- The luminosity upgrade goal value $\Delta\nu^e_z$=0.04 (corresponding to an increase by about 24%) will be quite challenging.
- Machine commissioning for polarisation will be in practice more difficult than in the past.

10 REFERENCES

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HERA Strahlkontrollen, neue Wechselwirkungszonen

Frank Stulle
Grömitz, September 2000

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