LONGITUDINAL POSITRON POLARISATION IN HERA–II

The HERA team, DESY, Hamburg, Germany

Abstract

With the installation of two pairs of spin rotators around the $p/e^{\pm}$ Interaction Points (IP's) North and South, longitudinal $e^{\pm}$ spin polarisation has now become available for the HERA collider experiments H1 and ZEUS, allowing the exploitation at high energy of the sensitivity of the scattering cross sections to the $e^{\pm}$ helicity. We describe the measures needed to attain polarisation in light of the HERA Upgrade and the resulting recent performance.

INTRODUCTION

HERA is a 6.3 km long $p/e^{\pm}$ double ring collider. The proton and $e^{\pm}$ beams are accelerated up to 920 GeV and 27.5 GeV respectively and collide head–on at the IP's North and South, where the experiments H1 and ZEUS are located. The internal gas target experiment HERMES joined the collider experiments in 1994.

An integral part of the original HERA design was the provision of longitudinally spin polarised $e^{\pm}$ beams for the collider experiments. In a high energy storage ring, $e^{\pm}$ beams can become spin polarised through the Sokolov–Ternov effect[1]. The polarisation direction is given by the periodic solution, $\hat{n}_0(s)$, of the Thomas–BMT equation for the spin on the closed orbit, and it is vertical in a perfectly planar ring with no solenoids. $\hat{n}_0(s)$ is rotated into the longitudinal direction at the experiment location by special magnet insertions ("spin rotators") which, at HERA, make use of radial fields. The ring is therefore no longer planar everywhere. In a ring where, by design, $\hat{n}_0(s)$ is not everywhere vertical and/or there is, by design, vertical dispersion, stochastic photon emission causes the single particle spins to diffuse away from $\hat{n}_0(s)$ with a consequent decrease of polarisation. This source of spin diffusion is partially neutralised in a "spin matched" optics[2, 1]. Spin diffusion is also caused when the tilt of $\hat{n}_0$, $\delta\hat{n}_0$, and the vertical dispersion are non–zero due to the unavoidable magnet misalignment and field errors [1]. As predicted by simulations, for HERA a $\delta\hat{n}_0(s)$ of some tens of mrad leads to very large depolarisation. Thus in addition to the usual orbit correction, a dedicated minimisation of $\delta\hat{n}_0(s)$ is needed. At HERA this is realised empirically by minimising the most important Fourier components of $\delta\hat{n}_0(s)$ by means of vertical orbit bumps ("harmonic bumps")[3] on the basis of the polarisation measurement.

Spin diffusion is particularly strong when the spin tune [1] ν_{sp} fulfils the resonance condition $\nu_{sp} \pm m\nu_x \pm n\nu_z \pm p\nu_s =$ integer, where $\nu_{x,z,s}$ are the orbital tunes and m, n, p are integers. The resonances are strongest at low order ($\equiv |m| + |n| + |p|$) and these must therefore be avoided.

Finally, in a collider like HERA, the interaction with the counter–rotating beam is also expected to be a source of depolarisation. The proton bunches act as non–linear lenses causing a shift and a spread of the $e^{\pm}$ tunes; in addition the fields of the proton bunches directly perturb the orbital and spin motion of the single $e^{\pm}$, thereby disturbing the spin matching. The orbital tunes are chosen so to optimise the polarisation. Due to the large beam–beam tune shifts it can happen that the tunes of the pilot bunches (i.e. the few non–colliding bunches used for the background correction of the luminosity measurement) then lie on a spin–orbit resonance.

After high transverse polarisation was demonstrated at HERA, the HERMES experiment was installed at the IP East during the 1993–1994 shut down together with a pair of spin rotators around that IP to provide the experiment with longitudinally polarised $e^{\pm}$ beams[4]. The spin helicity can be inverted at the IP by inverting the directions of the radial fields of the rotator magnets. Until August 2000, careful machine tuning (orbit, energy, orbital tunes) allowed high (between 50% and 70%) longitudinal polarisation to be delivered to HERMES, as well as luminosity for H1 and ZEUS. The steadily increasing strength of the beam–beam interaction[5] could also be handled. On the basis of this success two more pairs of spin rotators were prepared for H1 and Zeus and installed between September 2000 and July 2001 when the Interaction Regions (IR) were rebuilt with the aim of getting a challenging factor of 5 higher luminosity[6].

Today HERA–e is still the only high energy $e^{\pm}$ ring delivering longitudinal spin polarisation.

IMPACT OF THE LUMINOSITY UPGRADE ON POLARISATION

A detailed account of polarisation calculations for the Upgrade is given in[7]. The main concerns were the removal of the experiment anti–solenoids, the overlapping of the strong combined function magnet GO and the H1 solenoid field, the increased strength of the IR and arc quadrupoles resulting in a larger sensitivity to magnet misalignment, and the increased beam–beam interaction strength. Assuming $I_p = 140$ mA the incoherent horizontal and vertical tune shifts per IP, $\Delta\nu^{inc}_{x,z}$, were expected to increase w.r.t. year 2000 from 0.012 to 0.034 and from 0.029 to 0.052 respectively.

After removal of the anti–solenoids, the insertion of the two more pairs of spin rotators, which decreased the maximum attainable level of Sokolov–Ternov polarisation from 89%

[1] ν_{sp} is the number of precessions around $\hat{n}_0$, per revolution, performed by a spin nonaligned with $\hat{n}_0$; at HERA at 27.5 GeV it is about 62.5.

to 83% and introduced further potential sources of depolarisation, was not only suitable for the experiments, but also necessary for the survival of polarisation. The H1 solenoid, for example, would tilt an initially vertical $\hat{n}_0$ by about 86 mrad, thus destroying polarisation. The GO/H1 solenoid field overlap leads to a small $\hat{n}_0$ tilt even in the presence of the rotator.

In the current design the betatron coupling resulting from the solenoids is corrected by four independently powered skew quadrupoles per IP. Their strengths are trivially computed by requiring the off diagonal blocks of the transport matrix through the IR to vanish. Since the solenoids are relatively weak (7.6 Tm and 4.4 Tm for the H1 and Zeus solenoids respectively) their treatment as small perturbations is adequate. Because the knowledge of these fields is not very accurate, orthogonal knobs for an empirical correction of the coupling based on[8] were also provided[7] and proved to work well.

Fig. 1 shows polarisation vs. energy for the optics with 3 rotator pairs and no misalignments (linear calculations with SLIM[9]): (a) ideal optics; (b) optics with H1 solenoid turned on; (c) with H1 solenoid turned on, after correcting its effect on orbit, coupling and $\hat{n}_0$. The three dashed lines correspond to the polarisation related to each of the three degrees of freedom of the motion. The effect of random alignment errors for the upgraded 3-rotator optics including the experiment solenoids was studied with SITF[10]. Results are summarised in Table1. The assumed r.m.s. value of the horizontal and vertical quadrupole displacement is 0.3 mm with a 3 σ cut. The results are averaged over 6 seeds. The orbit has been corrected down to 0.8 mm in both planes.

after usual orbit correction		with $\delta\hat{n}_{0,rms}$ minimisation in addition	
$\delta\hat{n}_{0,rms}$ (mrad)	P_{lin} (%)	$\delta\hat{n}_{0,rms}$ (mrad)	P_{lin} (%)
32.9±7.6	10.3±5.5	14.8±3.7	63.8±2.1

Table 1: Expected $\delta\hat{n}_{0,rms}$ and polarisation in the presence of random errors.

It is worth noting that without the experiment solenoids P_{lin} increases to 67.5% $\pm$ 4.8.

The expected polarisation in the presence of non–linear spin motion, computed by SITROS[10] for the same 6 seeds, is 57%$\pm$ 3.2. This number does not include beam–beam effects, since the code could not deliver convincing results for the upgraded optics in the presence of beam–beam interaction. On the basis of the pre–Upgrade observations the maximum attainable polarisation in the presence of the beam–beam interaction can be estimated to be around 45-50%.

As expected, the $\delta\hat{n}_0$ is larger than in the pre–Upgrade optics and therefore the orbit must be better corrected and eight $\delta\hat{n}_0$ Fourier components (instead of four) must be minimised to get $P_{lin} \geq$ 60%.

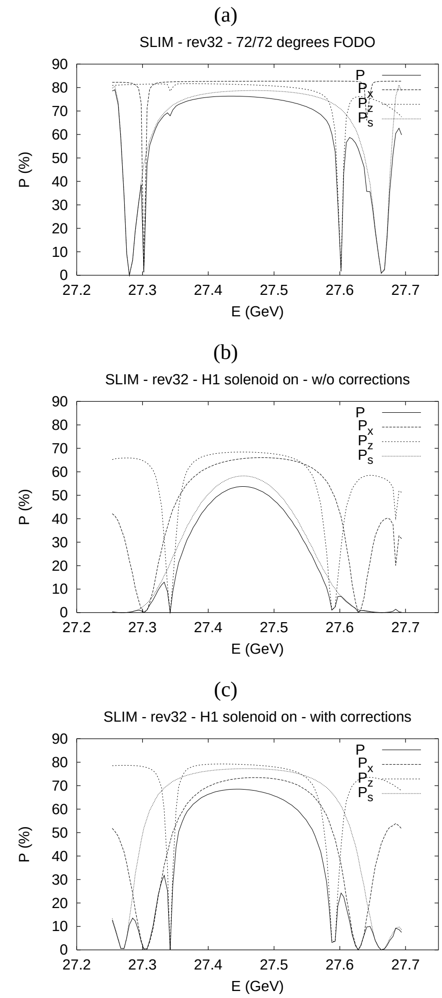

Figure 1: Polarisation vs. energy with no misalignments (linear spin motion calculations).

POLARISATION OPERATION IN THE UPGRADED MACHINE

The first polarisation studies with all three rotators turned on took place with e^+ and without collisions, in the last week of February 2003, before a shutdown. All eight harmonic components could be optimised. The maximum longitudinal polarisation attained (with experiment solenoids turned on) was 54%, close to expectations.

After this “proof of principle”, the concern was of course to keep polarisation high during normal luminosity operation, not only because of the beam–beam interaction, but also because of the observed large run-to-run orbit excursions. These orbit effects were new for HERA and are due mainly to the relatively flexible supports of the new IR magnets. To keep the e^+ orbit under control, orbit feedback was brought in operation in 2003. Simulations show that the orbit feedback is beneficial for polarisation too[11].

Since operation resumed after the 2003 shut-down, polarisation has been optimised mostly parasitically during luminosity operation. This is not simple because the empirical

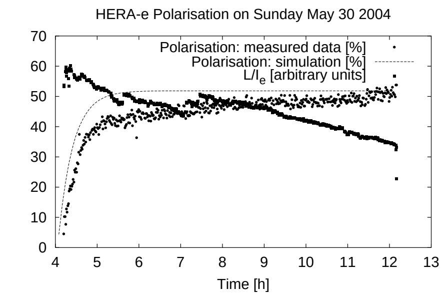

Figure 2: Measured polarisation and L/I_e (arbitrary units) vs. time; the dashed curve shows simulated data: polarisation grows more slowly than expected from the Sokolov–Ternov effect.

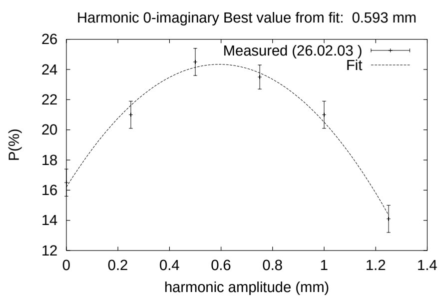

Figure 3: Measured polarisation vs. harmonic bump amplitude for the harmonic 0 imaginary.

optimisation requires time and polarisation may increase as an effect of the decreasing beam–beam forces during the run. Fig. 2 shows measured polarisation vs. time during a luminosity run: polarisation increases more slowly than expected from the Sokolov–Ternov effect (the dashed curve), suggesting that the asymptotic polarisation value itself is increasing with time. It is difficult under such conditions to estimate the optimum value of the harmonic bumps, in particular of those, namely -1 and $+2$, in the HERA convention, having a broad maximum (compare Fig. 4 with Fig. 3). Fig. 2 also shows the measured luminosity divided by the electron current (arbitrary units), a parameter therefore proportional to the beam–beam force experienced by the e^+ beam. Total beam-beam tune shifts as high as 0.013 (horizontal) and 0.040 (vertical) have been measured with $I_p \simeq$ 80 mA (the measured tune shifts are expected to be half of the incoherent values).

Currently, the longitudinal polarisation delivered in the presence of collisions is around 40%, increasing to 50% toward the end of a run (see Fig. 2). Fig. 5 shows the peak polarisation vs. run number since the end of February 2004 when we returned to using the design bunch number.

SUMMARY

The Luminosity Upgrade design has been optimised for the highest improvement in luminosity but is not optimal

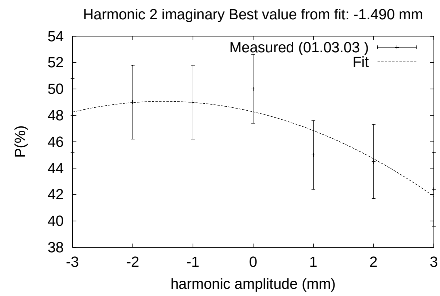

Figure 4: Measured polarisation vs. harmonic bump amplitude for the harmonic +2 imaginary.

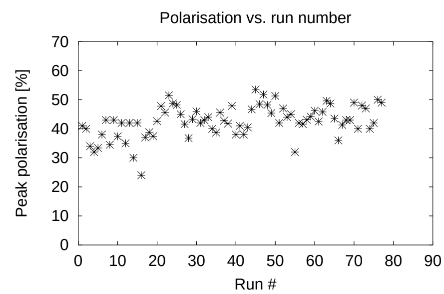

Figure 5: Measured peak polarisation vs. run number.

for polarisation. The maximum attained polarisation (54 %) without collisions is close to expectations. The routinely delivered longitudinal polarisation in the presence of collisions depends upon the proton current and emittance and is currently between 40% and 50%.

REFERENCES

[1] D.P. Barber and G. Ripken, in *Handbook of Accelerator Physics and Engineering*, Eds. A.W. Chao and M. Tigner, World Scientific, 2nd edition (2001) 155-167.

[2] A.W. Chao and K. Yokoya, KEK TRISTAN Report, 81-7 (1981).

[3] D.P. Barber et al., *Nucl. Instrum. Methods* A **338**, 166-184 (1994).

[4] D. P. Barber et al., *Phys. Lett.* B **343**, 436-443 (1995).

[5] E. Gianfelice, in *Polarised protons at high energies,* DESY-PROC-1999-03, 77-91 (1999).

[6] M. Seidel and F. Willeke, "Layout of the Upgraded HERA Interaction Regions", EPAC'00, Wien, June 2000.

[7] G.Z.M. Berglund, "Spin-orbit maps and electron spin dynamics for the luminosity upgrade project at HERA", DESY-THESIS-2001-044 (2001).

[8] M. Bassetti, CERN ISR-TH 79-41 (1979).

[9] A. W. Chao, *Nucl. Instrum. Methods* A **180**, 29-36 (1981).

[10] J. Kewisch, DESY 85-109 (1985).

[11] E. Gianfelice, DESY-HERA-03-18, (2003).