POLARIZATION AT HERA [1]

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Abstract

The status of the HERA project is briefly reviewed and the plans for obtaining longitudinal polarization are described.

THE MACHINE

HERA, the high energy electron-proton colliding beam facility that has been constructed at the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg, Federal Republic of Germany will be commissioned early in 1991 and will be ready for data taking later in that year[1].

The electrons and protons are stored in separate vacuum pipes 6336 m in circumference and will have energies of (up to) 35 GeV and 820 GeV respectively. The luminosity at each interaction point will be about 1.5×10^{31} cm^{-2} sec^{-1}. Figure 1 shows a plan view representation of the machine. The ring tunnel is 10 - 20 m underground. Construction began in May 1984 with the electron ring being completed in 1988 and the last magnet of the proton ring, which relies on superconducting magnets, being installed in September 1990. The countries participating in the construction are Germany, Canada, Czechoslovakia, France, The Netherlands, Israel, Italy, Poland, the Peoples' Republic of China, the United Kingdom and the United States of America. The electron beam was commissioned in August 1988 and in September 1989 ten times the design single bunch current was stored at the then maximum energy of 27.5GeV. More details may be found in Ref. 1 and the HERA proposal[2].

One of the most important features of HERA is that it has been designed with the aim of storing spin polarized electrons and achieving longitudinal polarization at the interaction points. However, before entering into this, the main topic of this talk, I shall briefly review the physics program.

PHYSICS AIMS

HERA is primarily a tool for studying the deep inelastic structure of protons and perhaps quarks by exchange of virtual photons and weak bosons. The c.m. energy extends

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up to 314 GeV and the energy transfer, ν, to the protons extends up to 52 TeV. Clearly, HERA provides for a huge expansion of the accessible region of exploration beyond that available with fixed target experiments[3]. Electron spin polarization will make possible tests of helicity dependences expected in the Standard Model of weak and electromagnetic interactions[4] and will be needed in searches for right handed weak currents and supersymmetric interactions. Studies of the q^2 dependence of structure functions will enable quark substructure to be investigated. Detailed measurements on weak interactions effects will be sensitive to the existence of additional Z^0 and $W^{\pm}$. These and other aspects of the physics programme are discussed in more detail in Ref. 3.

So far, two experiments have been approved for HERA, namely "H1" and "ZEUS". They are being installed in the North and the South interaction regions respectively and both are designed to do the kind of physics described above. A third experiment, "HERMES", is currently being considered[5] for installation in the East straight section with the aim of making a very detailed study of the spin structure of nucleons[6] by scattering longitudinally polarized electrons off of polarized stationary nucleons.

Further details can be found in the proposal documents[5,7].

POLARIZATION

That electrons in storage rings could become self polarized was first noted by Loskutov, Korovina, Sokolov and Ternov[8], who pointed out that the emission of synchrotron radiation in a simple storage ring can cause electron spins to flip from up to down and vice versa and that there is a difference in the rates. Only a very small fraction of the synchrotron radiation[9] power causes spin flip so that the polarization process tends to be slow on the time scale of other dynamical phenomena. Nevertheless this asymmetry in the rates should lead to a build up of polarization along the vertical guide field. The equilibrium polarization should be $P_{eq} = \frac{8}{5\sqrt{3}} = 92.4\%$ and the time constant for the exponential build up should be[9]

$$\tau_p^{-1} = \frac{5\sqrt{3}\gamma^5 \hbar e^2}{8\rho^3 m^2 c^2} \tag{1}$$

where γ is the Lorentz factor, ρ is the radius of curvature in the magnets and the other symbols have their usual meanings. At HERA the time constant is 40 mins and 11 mins at 27 and 35 GeV respectively.

Natural polarization was first detected at ACO and Novosibirsk[10]. It has also been seen at CESR, SPEAR, VEPP2M, VEPP4[10,11,12] and at DESY at the PETRA and DORIS rings[13] where valuable experience was gathered and vertical polarizations of over 70 % and of over 80 % at beam energies of 16.5 and 5.01 GeV respectively have been observed. At this Conference we received the happy tidings that vertical polarization had been observed at LEP and TRISTAN[14,15].

The original treatments of Ref. 8 concerned themselves with uniform magnetic fields. In real rings however, as well as the vertical fields, there are drift spaces and horizontal and even longitudinal fields. In addition, the electrons oscillate around the central orbit. Thus a more complete treatment is needed and this begins with a study of spin precession in general fields.

It is well known that a classical spin magnetic moment precesses around a static magnetic field. The polarization vector, defined in the rest frame, of a relativistic electron in a storage ring also precesses, but this time according to the Thomas-BMT equation[16]

$$\frac{d\overline{P}}{ds} = \frac{e\overline{P}}{mc\gamma} \times ((1+a)\underline{B}_{\|} + (1+a\gamma)\underline{B}_{\perp}) \ , \quad a = \left(\frac{g-2}{2}\right) \tag{2}$$

where $\underline{B}_{\|}$, $\underline{B}_{\perp}$ are the magnetic fields parallel and perpendicular to the trajectory , s is the longitudinal coordinate and g is the electron g factor.

An essential consequence of Eq.(1) is that for motion in a transverse magnetic field, the spin precesses around the field relative to the orbit at a rate which is $a\gamma$ faster than the rate of rotation of the orbit direction.

The number of spin rotations per turn around the ring, ν, is called the spin tune and represents the natural spin precession frequency of the system. Away from integer values of ν, a stable unique periodic solution of Eq. (1) on the closed orbit exists and is denoted as $\hat{n}_0$. In a flat ring $\nu = a\gamma$, $\hat{n}_0$ is vertical and so is $\vec{P}_{eq}$. In real machines with horizontal fields, $\hat{n}_0$ is no longer everywhere vertical but $\vec{P}_{eq}$ is still parallel to $\hat{n}_0$. Thus we know the direction of the polarization vector in the general case also. For particles on quasi-harmonic betatron trajectories, we can construct analogously quasi-periodic solutions denoted as $\hat{n}$. Under Fourier analysis these solutions contain only betatron harmonics and harmonics reflecting the ring layout[17]. They are no longer uniquely defined if the resonance condition

$$\nu = k + m_x Q_x + m_z Q_z + m_s Q_s \ , \tag{3}$$

(where k, m_x, m_z, m_s are integers, and the $Q_{x,z,s}$ are orbital tunes) is satisfied. We return to these solutions below.

At HERA we require longitudinal polarization at the interaction points but since (see Eq. (4) below) the polarization vector must be vertical in the arcs in order to 'drive' the polarization process, it is then necessary to rotate the polarization from vertical to longitudinal just before the interaction points and back to vertical afterwards. In other words we must set up the magnetic field on the design orbit so that $\hat{n}_0$ has the correct azimuthal dependence. The Thomas-BMT equation tells us how to go about designing the required 'spin rotators': At HERA, $a\gamma$ is of order 70 and thus a small change in the orbit direction can cause a large tilt of the spin.

At HERA, the 'Mini-Rotator' design of Buon and Steffen has been adopted[18]. This consists of a string of interleaved vertical and horizontal bending magnets for which the non-commutation of large rotations about mutually orthogonal axes is used to tilt the spin into the horizontal plane in as short a distance as practical with as small a vertical excursion as possible. The horizontal bends replace the bend angle of one arc cell and the whole rotator is inserted into the end of the arc with minimum disturbance to the rest of the machine. The total vertical bend of this rotator is zero, so that the straight section is in the horizontal plane, and it is only 60 m long so that it is possible to create an optics in which no quadrupoles need be included among the constituent dipoles. By mounting the dipoles on coupled mechanical jacks and by having flexible joints between sections of vacuum pipe, it is possible to tune the rotator to give the correct spin transformation over the range 27-36 GeV and by reversing the vertical bend polarities both helicity states can be obtained. One pair of these rotators has been delivered and one complete rotator is undergoing mechanical tests at DESY prior to insertion in the tunnel. They are the first ever rotators to be realised at a storage ring. Figure 2 shows a rotator under test and set up for one particular helicity state.

So far, we have considered only the natural polarization process. However, electron orbits experience stochastic disturbance due to photon emission and there are damping processes. The balance of the two effects produces a stable phase space distribution. In a naive classical picture where spins ride on electrons one would expect also the spins to 'see' stochastic magnetic fields in the quadrupoles and that the spins would then diffuse or depolarize[9,19].

This can indeed happen: Synchrotron radiation can create polarization but it can also lead to its destruction! The final equilibrium polarization depends naively on the relative magnitudes of the two effects and since they can be comparable, it is essential to understand the details and to find methods of computation.

The first computer program which could digest a standard optic file and then analytically compute depolarization effects in the above simple picture was SLIM by Chao[9]. One is not surprised to discover that the spin diffusion effects are strongest and hence the polarization small when the resonance condition of Eq. (3) is satisfied. However, the SLIM formalism linearises the 3-dimensional spin motion and as a direct result only the lowest order resonances with m_x or m_z or $m_s = \pm 1$ are predicted[20].

But, it is not necessary to appeal to naive pictures of classical spins riding on electrons and then somehow mix this in with a quantum mechanical picture of spin flip: A complete semi-classical quantum mechanical treatment which takes account of the various effects in a unified way has been given by Derbenev and Kondratenko as long ago as 1973 and Mane in 1987[21,22]. They give the following expression for the equilibrium polarization

$$P_{eq} = \frac{8}{5\sqrt{3}} \frac{\langle \frac{1}{|\rho|^3} \hat{b} \cdot \left[\hat{n} - \gamma \frac{\partial \hat{n}}{\partial \gamma} \right] \rangle}{\langle \frac{1}{|\rho|^3} \{ 1 - \frac{2}{9} (\hat{n} \cdot \hat{v})^2 + \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2 \} \rangle} \tag{4}$$

where $\hat{n}$ has been defined above and $\hat{b} = \bar{v} \times \dot{\bar{v}} / \mid \bar{v} \times \dot{\bar{v}} \mid$ where $\bar{v}$ is the particle velocity. The angle brackets denote a ring and ensemble average and $\gamma\ \partial\hat{n}/\partial\gamma$ is a partial derivative with respect to energy encapsulating the quantum mechanics of the effect of the orbit motion on the spin. Thus in this formalism, it is this quantity which describes the depolarizing effects. In a perfectly aligned flat machine, $\hat{n}$ is vertical and parallel to the guide field and $\gamma\ \partial\hat{n}/\partial\gamma$ is zero leaving just the natural polarization component which gives 92.4% as before. In real machines $\gamma\ \partial\hat{n}/\partial\gamma$ can be large. It is particularly large when the resonance condition of Eq. (3) for the spin tune ν is satisfied, but in contrast to the SLIM picture, this now comes about because $\hat{n}$ is not well defined at resonances[17]. Furthermore, in principle, resonances can appear for all integers m_i in Eq. (3). P_{eq} is then small.

Mane has written the first program, SMILE, for calculating $\hat{n}$, $\gamma\ \partial\hat{n}/\partial\gamma$ and hence the polarization, which operates on standard optic files. The calculations are *analytical* and are based on a perturbation expansion for $\hat{n}$. It can be set to calculate the polarization to arbitrarily high order in the resonance structure and by definition automatically includes all resonance interference effects. In this formalism it becomes immediately clear that although based on a different picture, SLIM calculations correspond algebraically *exactly* to the lowest (first) order version of the general theory.

Previously, it was only possible to make general qualitative statements about restricted catagories of the higher order effects[10,23]. To come further, one used the Monte Carlo tracking simulation, SITROS, written at DESY, to track classical spins numerically with built in radiation effects[24]. More recently Buon has extended the original spin diffusion picture of SLIM to higher order in the classical spin motion[25] and a further quantum mechanical treatment has been given by Hand and Skuja[26].

Away from resonances, $\hat{n}$ is closely parallel to $\hat{n}_0$ and the numerator in Eq.(4) shows that to obtain high polarization, $\hat{n}_0$ must be fairly parallel to the guide field in most of the ring i.e. the Sokolov-Ternov 'driving' effect must be maximised. $\hat{n}_0$ also defines the direction of the ensemble polarization vector. We can now see that in machines with dipole rotators, the maximum achievable polarization will be below 92.4%. At HERA, with two rotator pairs in the ring, the maximum polarization would be about 87%.

These theoretical maxima can only be achieved if $\gamma\ \partial\hat{n}/\partial\gamma$ is small at those places in the ring where $1/\rho^3$ is large. Furthermore, $\gamma\ \partial\hat{n}/\partial\gamma$ increases with energy!

So what level of electron polarization can we expect at HERA?

Inspection of the perturbation theory for $\hat{n}$ shows that $\gamma\ \partial\hat{n}/\partial\gamma$ depends on multiple integrals which describe how the spin motion is coupled to and driven by the orbital motion. Each integral increases with energy and is to be multiplied by a factor which resonates at the resonance energies of Eq. (3). At lowest (SLIM) order one has single one-turn integrals over products of orbital and spin functions. In machines with a longitudinal or horizontal component of polarization in the straight sections on either side of the IP and/or with vertical dispersion, i.e. in any machine with dipole spin rotators, some of these one-turn integrals can be large and as a result, even at SLIM level, there is no hope of obtaining significant polarization without making special arrangements. These consist of carefully choosing the geometry and the designing of sufficient flexibility into the optics and the power supply layout so that the optics can be adjusted to bring the relevant integrals to zero. Naturally, the resulting optic must be acceptable on all other grounds such as aperture requirements, tunes etc etc. Thus, even at the lowest order in the theory, the minimizing of depolarizing effects has a major influence on the design of the machine and severely constrains the optics. In the current jargon, these manipulations are called 'first order spin matching'[27].

At HERA the above factors have been catered for and good, but not perfect, first order spin match solutions can be found for the rotator systems proposed and as expected, for a *perfectly* aligned machine, SLIM predicts high polarization (i.e. 87%) with some remaining weak resonances. These comments are illustrated in figure 3 where the polarization calculated with SLIM for a perfectly aligned HERA before (lower curve) and after (upper curve) spin matching are shown.

Of course, HERA, like other machines cannot be perfectly aligned: The closed orbit is always distorted by a millimetre or so and quadrupoles are always slightly twisted. The distorted closed orbit causes $\hat{n}_0$ to be tilted from the vertical by a few milliradians in the arcs and results in spurious vertical dispersion and these immediately cause some 'dormant' spin-orbit integrals to be non-zero so that large additional terms appear in $\gamma\ \partial\hat{n}/\partial\gamma$. Thus our previous spin match is partly destroyed and since machine distortions are, by their very nature, irregular and difficult to control, we are, even at lowest order, confronted with a potentially uncontrollable source of depolarization. At SLIM order the result would look something like the lower curve in figure 3 again.

Luckily, there are algorithms for adjusting the closed orbit so as to minimize the tilt of $\hat{n}_0$ and the spurious dispersion and these offer a way to regain some control. Such methods were successfully used at PETRA at 16.5 GeV to obtain over 70% polarization[13,28] and updated methods are being developed for HERA too[29,30].

What do analytic calculations *beyond* SLIM predict for HERA? Calculations with SMILE show that high order resonances can be very dangerous and a careful analysis of this algorithm[31] or of the formalism of Buon[25], makes the reason clear: The majority of the dangerous resonances are synchrotron (Q_s) sidebands of parent Q_x, Q_z and Q_s resonances resulting from the fact that there is an energy spread and that the spin tune is frequency modulated at the synchrotron tune as a result of synchrotron motion in the beam[31,32].

The strength of the sidebands can be quantified. The relevant parameter is the modulation index:

$$\alpha = (\frac{a\gamma\frac{\sigma_E}{E}}{Q_s})^2 \tag{5}$$

The sideband strengths depend on powers of α. α is clearly a strongly energy dependent quantity and, in order to control the synchrotron sidebands it must be made as small as possible. At HERA, at 29GeV and with a Q_s of 0.06, α is 1.4 and calculations with SMILE show little residual polarization – the sidebands are very strong. Similar indications are given by SITROS. However, if Q_s is increased to 0.1 so that α is reduced, SMILE shows the expected dramatic improvement. Thus we will make every effort to run HERA at high Q_s. Figure 4 shows a polarization curve for a *perfectly* aligned HERA with two rotator pairs after spin matching and with $Q_s = 0.1$.

The potential for spin tune modulation to cause trouble has been known for many years. But the predictions were always qualitative. Now, with analytical calculations on real optic files the picture is much clearer.

Nevertheless, owing to the unavoidably imprecise nature of the description of the magnet field structure and particle dynamics in storage rings, calculations of polarization can, at very best, only yield approximate information which can help in the optimization and design of the machine. The real picture can only emerge from measurement.

At HERA, the vertical polarization will be measured by Compton back scattering of circularly polarized laser light off of the electron beam and measuring the up/down asymmetry of the scattered photons. More details of this technique can be found in references 14,15 and 33.

CONCLUSIONS

In conclusion then, the achievement of self polarization at high energy presents a challenge which will require unaccustomed machine tuning and the accumulation of experience but we draw strong encouragement from the recent observations at LEP and TRISTAN.

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Fig. 1 Schematic view from above of the HERA ring and preaccelerators. .

Fig. 2 A "MiniRotator" on test.

Fig. 3 Calculations with the program SLIM for a typical electron optics before (lower curve) and after (upper curve) spin matching.

Fig. 4 High order calculation with the program SMILE corresponding to the upper curve of figure 3.