DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 86-170
December 1986

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by

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ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

DESY 86- 170
December 1986

ISSN 0418-9833

HERA AND POLARIZATION AT HERA*)

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*) Invited talk at the 7th International Symposium on High Energy Spin Physics, Protvino, USSR, September 1986

Abstract

A report on the status of the HERA project is presented. The machine, the proposed experiments and the plans for longitudinal polarization are described.

The machine

HERA is a high energy electron (or positron)-proton colliding beam facility that is being constructed at the Deutsches Electron Synchrotron (DESY) laboratory in Hamburg, Federal Republic of Germany. The name HERA is short for Hadron Electron Ring Anlage.

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 $1.5 \cdot 10^{31} cm^{-2} sec^{-1}$. Fig. 1 shows a plan view representation of the machine. The ring tunnel is 10-20 m underground. Construction began in May 1984 and we hope to have colliding beams in 1990. The countries participating in the construction are Germany, Canada, France, Holland, Israel, Italy, Poland, People's Republic of China, Switzerland, United Kingdom and United States of America.

Electrons and protons will be supplied with the aid of a modified version of the existing storage ring PETRA and this in turn will be receive them from a series of purpose built lower energy machines. More details may be found in the HERA proposal[1].

HERA incorporates a number of special features.

The high proton energy requires that the proton ring will use superconducting magnets. Among these, the dipoles are 9 m long and run at 4.5 T.

HERA is being designed with the aim of storing polarized electrons and achieving longitudinal polarization at the interaction points.

Tracking simulations of the beam dynamics have shown[2] that the electrons and protons must collide "head on" in order to avoid synchro-betatron orbit resonances which could destroy the proton beam.

This "zero angle" geometry requires that the electrons be deflected into the path of the protons and then out again with the aid of combined function quadrupoles positioned close to the interaction points/3/. Naturally, such an arrangement leads to engineering constraints and in particular in the West area where the electron and proton beams will be injected, it has been decided that during the starting up phase no electron-proton collision point will be provided.

Physics aims

Naturally, an important aim of a machine like HERA is to study deep inelastic e-p scattering as a means of probing the structure of quarks. The c.m. energy extends up to 314 GeV and the energy transfer, ν, to the protons extends up to 52 TeV. The accessible kinematic region in the Q^2-ν plot is the triangle in Fig. 2. The kinematically accessible region for 10^3 GeV electrons scattering on a fixed target is the shaded area in the lower left corner. Clearly HERA provides for a vast expansion of the accessible region and it is expected that in two years of data collection enough data should be available to explore distances down to $3 \cdot 10^{-18}$ cm. In addition, these structures can be explored not only by exchange of virtual photons but also with Z°, $W^\pm$. In particular Z° and γ will interfere and the helicity dependence of the weak couplings will lead to differences in the positive and negative helicity electron and positron cross sections (Fig. 3) and provide a further test of the standard model/4/. Polarization will also be used to search for right handed weak currents and for supersymmetric interactions. Studies of the Q^2 dependence of structure functions will enable quark substructure to be investigated. Detailed measurements on weak interaction effects will be sensitive to the existence of additional Z° and $W^\pm$. These and other aspects of the physics programme are discussed in more detail in Ref. 5.

The experiments

So far, two experiments have been approved for HERA namely "H1" and "Zeus". They will be installed in the North and South interaction regions respectively and both are designed to do the physics described above.

H1 is a collaboration of groups from Fed. Rep. Germany, France, German Dem. Rep., Italy, Switzerland, U.K., USA and USSR. Zeus is a collaboration from Fed. Rep. Germany, Canada, Holland, Israel, Italy, Poland, Spain, U.K. and USA.

Since the proton fragmentation products will be scattered mainly in the direction of the 820 GeV protons, both detectors are asymmetric in internal arrangement. Both utilize calorimeters for measuring the shower energies. H1 relies on liquid argon calorimetry and Zeus on uranium scintillator calorimeters. In both detectors it is important that for unambiguous identification of the kinds of events expected, all particle tracks are registered. Thus, an essential feature of both detectors is that they provide complete coverage. Both use transition radiation detectors in the proton direction to help discriminate electrons from hadrons. Further details can be found in the proposal documents/6/.

Polarization

The notion that electron beams in storage rings could become polarized originated with the work of Loskutov, Korovina, Sokolov and Ternov/7,8/ 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 visa versa and that there is a difference in the rates. Only a very small fraction of the synchrotron radiation power causes spin flip but nevertheless this asymmetry in the rates should lead to a build up of polarization along the vertical guide field. The equilibrium polarization should be $8/5\sqrt{3} = 92.4\ \%$ and the time constant for the exponential build up should be/8,9/

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

where γ is the Lorentz factor and ρ is the radius of curvature in the magnets. At HERA the time constant is 40 mins and 11 mins at 27 and 35 GeV respectively.

As is well known, a classical spin magnetic moment precesses around a static magnetic field. The polarization vector of a relativistic electron in a storage ring also precesses but this time according to the BMT equation/10/:

$$\frac{d\bar{P}}{ds} = \frac{e\bar{P}}{mc\gamma} \wedge \left[(1 + a)\, \underline{B}_{\parallel} + (1 + a\gamma)\, \underline{B}_{\perp}\right] , \qquad a = \left(\frac{g - 2}{2}\right)$$

$\underline{B}_{\parallel}$, $\underline{B}_{\perp}$ are the magnetic fields parallel and perpendicular to the trajectory and s is the longitudinal coordinate. In real storage rings there are quadrupole focussing magnets and possibly vertical bend magnets.

The electrons oscillate in the transverse fields of the quadrupoles and one expects, classically at least, that the polarization vectors will precess in the fields along the (oscillating) orbits. Thus, the theoretical description of the polarization mechanism, the calculation of its direction and of its equilibrium value is more involved than in the original treatments/8,9,11,12/.

If all effects are included one finds that the equilibrium polarization, $|\bar{P}|$, is given by the formula, originally derived by Derbenev and Kondratenko (D.K)/9/:

$$|\bar{P}| = \frac{8}{5\sqrt{3}} \; \frac{\langle |\rho|^{-3}\, \hat{B} \cdot (\hat{n} - \underline{d})\rangle}{\langle |\rho|^{-3}\, (1 - \frac{2}{9}\, (\hat{n} \cdot \hat{v})^2 + \frac{11}{18}\, \underline{d}^2)\rangle}$$

where $\hat{n}$ is a classical spin unit vector defined at each point in the (position, momentum) phase space of the particle ensemble and $\underline{d}(s) = \gamma \frac{\partial \hat{n}}{\partial \gamma}$ is a partial differential describing how $\hat{n}$ varies with particle energy ($\underline{d}$ depends on azimuthal position, s, in the ring).

The brackets, ⟨⟩, denote an ensemble and azimuthal average. This formula takes into account both the polarizing mechanism and the effect of particle oscillations (which are also excited by synchrotron radiation). A new derivation and elucidation of the D.K. formula has recently been given by Mane/13/ who derives it using quantum statistical arguments applied to the electron ensemble. If $\langle \underline{d}^2 \rangle$ is large then $|\bar{P}|$ is small.

$\underline{d}$ is particularly large when the natural spin precession frequency, ν, (the "spin tune") is near to the resonant condition

$$\nu = k + k_x\, Q_x + k_z\, Q_z + k_s\, Q_s$$

where the k's are integers and the Q's are the orbital tunes/9,12/. $\underline{d}$ is called the spin-orbit coupling vector. For a flat machine, $\nu = a\gamma$.

The direction of the polarization at each point in the ring is given by the unit spin vector, $\hat{n}_0$, which is the periodic solution to the BMT equation on the closed orbit:

$$\bar{P} = |\bar{P}|\; \hat{n}_0$$

The vectors $\hat{n}$ are closely parallel to $\hat{n}_0$. Thus, from the numerator of the D.K. formula one sees that to obtain high polarization it is essential for $\hat{n}_0$ to be parallel to the guide field in most of the ring. This is anyway its natural orientation in simple flat rings in which the dipole fields are all vertical.

At HERA, longitudinal polarization will be obtained by allowing $\hat{n}_0$ to remain vertical in the arcs and by rotating $\bar{P}$ (i.e. $\hat{n}_0$) into the horizontal plane just before the interaction point (I.P) and by returning it to vertical just after the I.P. The horizontal bend magnets in the interaction region then rotate $\bar{P}$ into and out of the longitudinal direction at the I.P. According to the BMT equation the spin precession angle in a transverse field is $a\gamma$ times larger than the orbit deflection angle. At 30 GeV, $a\gamma \sim 68$. Thus, small orbit deflections lead to large precession angles and since finite rotations do not commute, the required rotation can be achieved with the aid of a series of interleaved vertical and horizontal bends. This is the basis of the "Mini-rotator" scheme of Buon and Steffen/14/ which has been adopted for HERA. The layout of the ring near the I.P. is sketched in Fig. 4 where the horizontal (H) and vertical (V) rotator bends are marked. The bend angles depend on the electron beam energy. Helicity is reversed by reversing the vertical bend polarity. Thus, the beam pipe must be flexible and all rotator magnets mounted on adjustable jacks.

Since $\hat{n}_0$ is not parallel to the bending field except in the arcs, the maximum polarization (corresponding to $\underline{d} = 0$) is several percent less than 92.4 %.

To obtain high polarization it is still necessary to minimize $\langle d^2 \rangle$ at those points in the ring where $1/\rho$ in non-zero. If both orbital and spin motion are calculated in linear approximation one finds that $\underline{d}(s)$ can be written as a linear combination of one turn integrals whose integrands are products of orbital and spin motion factors[15]. Each integral is multiplied by a resonance factor leading to one of the linear resonances:

$$\nu = k \pm Q_i \;; \quad i = x, z, s$$

$\langle d^2 \rangle$ and the polarization can be calculated in linearized theory using the program SLIM[16]. For a normal "untreated" HERA electron optics the curve of calculated polarization versus energy often looks something like the lower curve in Fig. 5. In this example three pairs of rotators are switched on, the closed orbit is perfectly aligned and the maximum attainable polarization would be 85 %.

The polarization curve for this example falls off strongly on each side of the peak owing to strong Q_z resonance effects. The rotators have been adjusted to give longitudinal polarization at each energy.

One can then adjust the optics to minimize $\langle d^2 \rangle$. We call this procedure "spin matching" and at DESY this is carried out using the program SPINOR[17] of L. Hand.

The upper curve of Fig.5 shows the predicted polarization after spin matching this optics at 29.23 GeV. The polarization now reaches the full value of 85 % and although optimization (which is energy dependent) was carried out only at one energy this seems to be sufficient to ensure high calculated polarization over a broad range of energies. The dips are due to remaining resonance effects.

We cannot conclude from this, however, that we will achieve the full 85 % electron polarization at HERA. One should also include the effect of machine misalignments and mistuning, non-linear orbital and spin motion with their accompanying higher order resonances[12,18] and also beam-beam effects.

All of these can lead to a reduction of the polarization to below that predicted above.Techniques have already been developed for dealing with misalignments and mistuning[15,19]. Numerical studies of the other effects are in progress, in particular with the aid of the nonlinear spin-orbit tracking program SITROS[20,21]of J. Kewisch. The program SMILE[13] which is the natural extension of SLIM for including non-linear spin motion will also be very useful in this respect. It remains to be seen if higher order spin matching rules can be invented.

Conclusion

The HERA project is running according to schedule and two large high energy physics experiments are being prepared. The machine is being designed with the aim of achieving longitudinal electron polarization. This facility will be the first of its kind and high energy physics measurements will commence in 1990.

Acknowledgements

The author wishes to acknowledge the continued encouragement of Prof. G.-A. Voss and helpful discussions with colleagues, in particular, J. Buon, L. Hand, T. Limberg, J. Kewisch, R. Kose, H. Mais, S. Mane, G. Ripken, R. Rossmanith, K. Steffen, A. Skuja, G. Weber and G. Wolf.

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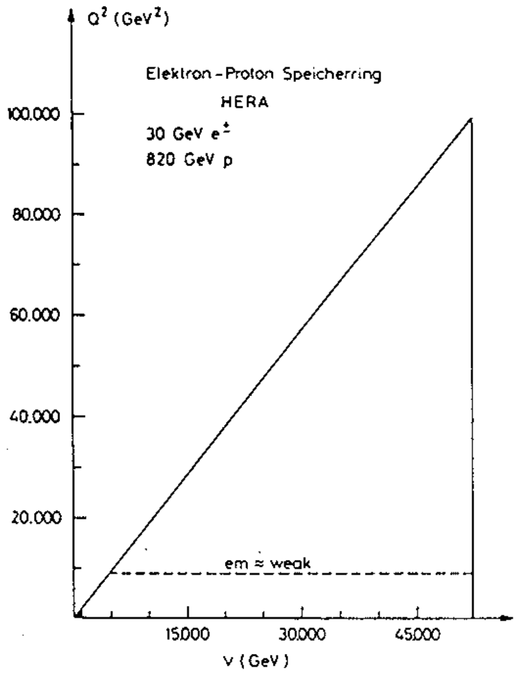

Fig. 2 The kinematical region available at HERA

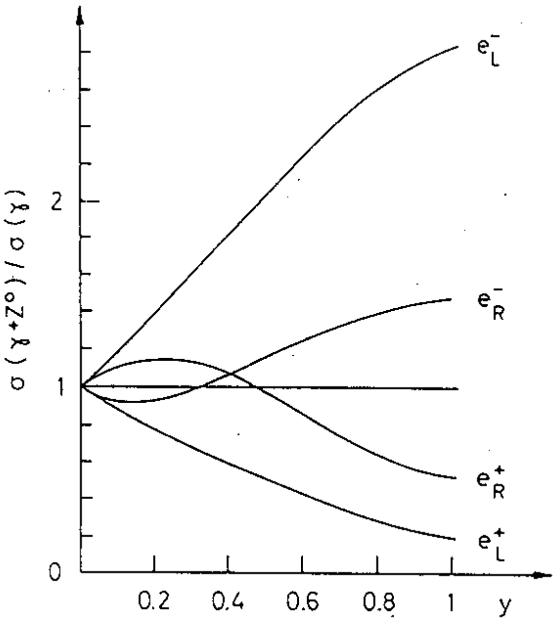

Fig. 3 Interference between photon and Z° exchange in the reaction $e + p \dashrightarrow e + X$ for electrons and positrons of positive and negative helicity. The cross section is normalized to the photon exchange cross section and plotted against the scaled energy transfer y for x = 0.25 (see ref.5)

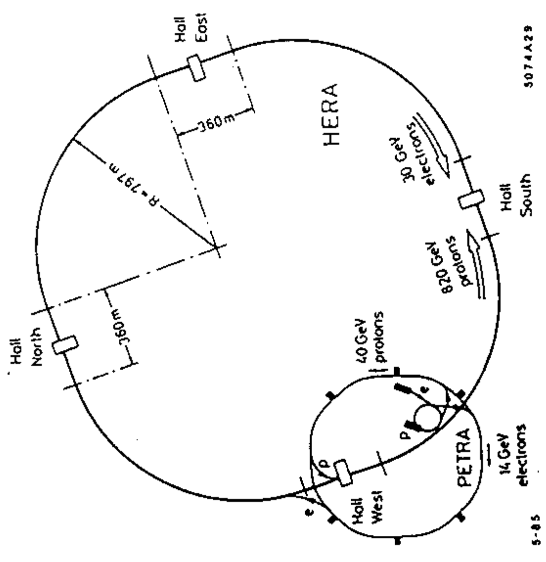

Fig. 1 Schematic view from above of the HERA ring and preaccelerators

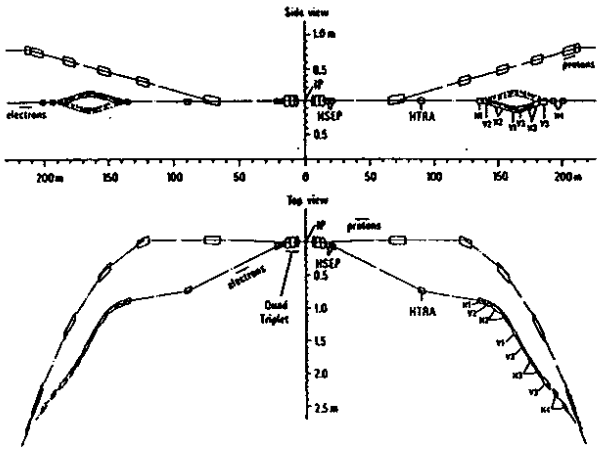

Fig. 4 Schematic plan and side views of the electron and proton rings at the normal straight sections.
The rotator bend magnets (H, V) are shown as are the separating magnets (combined function quadrupole triplet and dipoles)

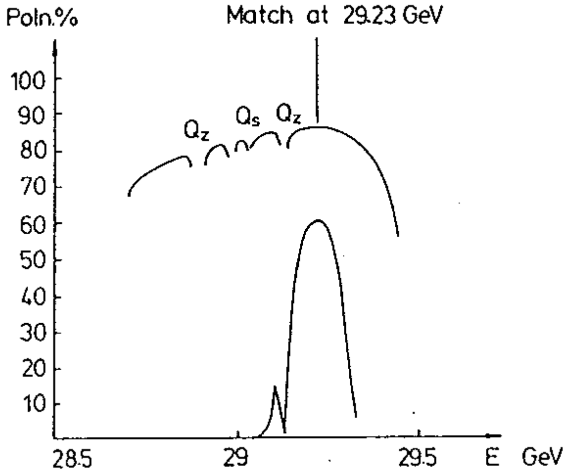

Fig. 5 Calculations with the program SLIM for a typical HERA electron optics before (lower curve) and after (upper curve) spin matching