The e-p Collider HERA

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Abstract
The construction of the electron-proton collider at DESY in Hamburg has been completed and the accelerator is now being commissioned. This paper describes the status and behaviour of the storage rings as of February 1992.

INTRODUCTION

HERA is the world's first electron-proton collider and the first accelerator built in an international collaboration where institutes in Canada, CFSR, China, France, Netherlands, Israel, Italy, Poland, UK and the USA have contributed either technical components or skilled manpower.

It is also the first time that large scale production of superconducting magnets has been done by industry.

Two storage rings are built in a 6.3 km long tunnel of 5.2 m diameter about 20 m below ground. The rings are designed to store 30 GeV electrons and 820 GeV protons respectively and to collide the two counterrotating beams head on in four interaction points spaced uniformly around the circumference.

The HERA project was approved in April '84, the tunnel was finished in August '87, the electron ring in August '88 and the proton ring in November '90 in accordance with the original time schedule and within the limits of the budget.

The first electron beam was stored in September '88, the first proton beam on April 14th 1991 and the first collisions occurred and the luminosity was measured on October 19th 1991.

At present the two large detectors are being brought into their final position at the interaction points North and South, and high energy physics runs are planned to start this summer.

Extensive details of machine components may be found elsewhere [1-7], thus only an overview of some important systems is presented here.

PREACCELERATORS

The layout of HERA with its preaccelerators is shown in fig. 1.

A whole new chain of preaccelerators has been built in order to inject protons into HERA.

The 50 MeV linear accelerator [8] for negatively charged hydrogen ions has been in routine operation since November 1988 and delivers a 10...15 mA 50 Us long beam pulse with a normalised 90 % transversal emittance of 3.3 π mm mrad in both directions and a momentum spread of ± 0.1 %.

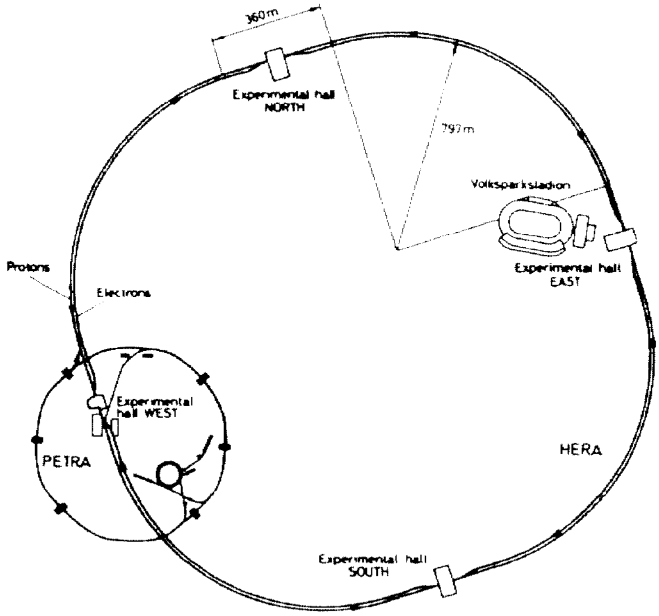

Fig. 1a: Layout of HERA

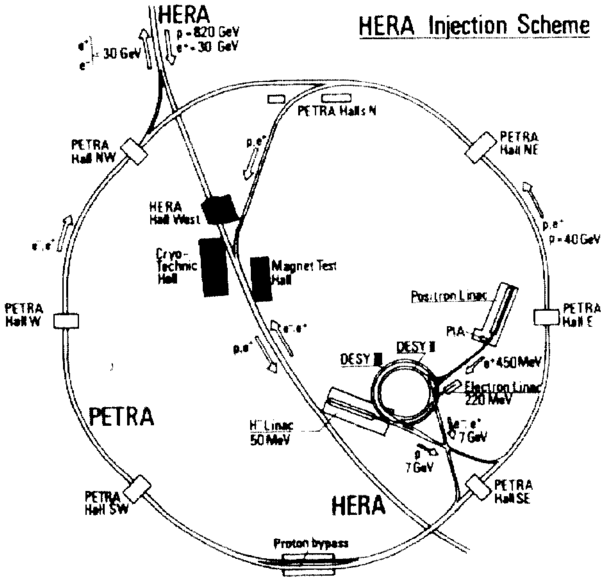

Fig. 1b: Layout of the HERA Preaccelerators

A stripping foil multiturn injection is used in DESY 3 [9], the protons are captured in 11 buckets, spaced 28.8 m apart as in HERA, accelerated to 7.5 GeV and ejected to PETRA 2. The design intensity of $1 \cdot 10^{11}$ protons per bunch can be injected and accumulated in DESY 3 but only $6 \cdot 10^{10}$ protons reach 7.5 GeV. The main loss occurs at flat bottom and is associated with space charge blow up and field nonlinearities reducing the dynamic aperture. The normalised transverse emittance at ejection is 3.6 π mm mrad horizontally, 5.4 π mm mrad vertically and the longitudinal emittance 0.1 eVs in rough agreement with the design value.

The maximum number of 70 bunches has been accumulated in PETRA 2 and accelerated to 40 GeV. The lifetime is 1 hour at 7.5 GeV and more than 10 hours at 40 GeV. The minimum cycle time of 5 minutes for protons is limited by nonlinearities caused by eddy currents in the thick aluminium vacuum chamber.

PETRA 2 has also to accumulate 30 electron or positron bunches. They are delivered as single bunches from the 400 MeV electron/positron LINAC 2, accumulated in the intermediate storage ring PIA and accelerated in the 7 GeV synchrotron DESY 2 with a repetition rate of 12.5 Hz.

Three feedback systems [10] are installed in PETRA 2 to damp transversal and longitudinal multibunch instability modes. Without feedback the multibunch current was limited by instabilities to 3 mA , whereas the single bunch current could easily exceed 5 mA. With feedback 60 mA in 30 bunches were reached.

REFRIGERATION SYSTEM[11,12]

The central helium refrigerator is subdivided into three identical plants each providing 6.6 kW isothermally at 4.3 K, 20.4 g liquid helium/second and 20 kW at 40 K to 80 K.

The cryogenic plant has been in almost continuous operation for 4 years and works very reliably.

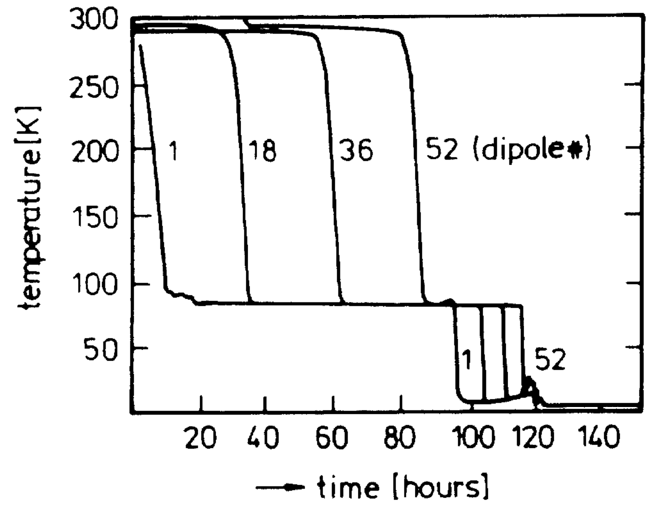

Fig. 2: Cooldown profile of a HERA Octant

Liquid and 40 K helium are supplied by a fourfold transferline to precoolers and feedboxes installed at the ends of each octant. The same transferline returns helium gas of 4.6 K and of 80 K to the refrigerator.

At the end of 1990 the complete proton ring was cooled down for the first time. A typical cooldown profile is shown in fig. 2. The cooldown time of 140 hours was choosen to limit the thermal stresses within the magnets to less than 50 % of the critical values. Instabilities or pressure oscillations have not been observed during 1 year of operation.

The heat load of the whole ring including transferlines and feedboxes was measured as 5.1 kW at 4.4 K and 28.5 kW at the shield level. These values compare favourably with the proposal values.

SUPERCONDUCTING MAGNETS[13]

A total of 2156 superconducting magnets and correction coils has been installed in the HERA proton ring. The cell structure in the arcs is schematically shown in fig. 3.

The industrial production of superconducting magnets was a success. During series production DESY received an average of 8 dipoles and 6 quadrupoles per week. Out of 449 dipoles and 246 quadrupoles only 5 magnets were rejected, four of which had shorted windings and one a bad spot in the superconductor.

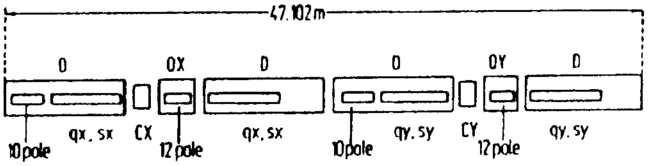

Fig. 3: A unit cell of the proton ring. D: main dipole; QX, QY: main quadrupole, qx, qy: correction coils, sx, sy: sextupole correction coils, CX, CY: correction dipoles. In addition, there are 10-pole and 12-pole correction coils.

All magnets were cold tested at DESY [14] to well above the design current of 5027 A. Nearly 93 % of the magnets reached the critical current at the first or second excitation cycle, the average quench current being (6900 ± 130)A for the dipoles and (7840 ± 160)A for the quadrupoles scaled to the ring temperature of 4.4 K.

The field quality of both the dipole and quadrupole magnets is better than specified.

Any change of the field in the magnets induces eddy currents within the filaments of the superconductor. These persistent currents degrade the field quality [15]. Their sextupole component enhances the uncompensated chromaticity of HERA at injection by more than a factor of five.

However the strength of the persistent current sextupoles varies little from magnet to magnet and is well reproducible. Therefore they can be compensated systematically by the multipole coils wound directly on the dipole beam pipes. Caused by flux creep in the superconductor and other effects the "persistent" currents decay with a nearly logarithmic time dependence [15]. This drift is also compensated using the correction coils.

In order to determine the required strength of the correction elements as a function of energy during machine operation the dipole and sextupole fields are measured continuously in cold reference dipole magnets powered in series with the ring magnets [16]. The strength of the sextupole component thus observed is plotted in fig. 4 for several magnet cycles of the type 244A-50A-1000A-50A-244A as measured in the reference magnets.

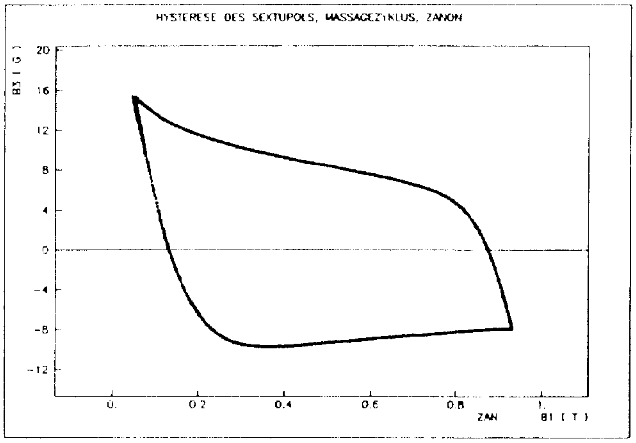

Fig. 4: Persistent current sextupole strength at r = 2.5 cm in Gauss measured with a rotating coil in the reference magnet and plotted versus the dipole field in T. Data from several magnet cycles are plotted.

The reference magnets also serve as an energy master. Their dipole field clocks all other magnet power supplies and the RF-frequency during ramping.

The energy stored in the magnets at 820 GeV exceeds 270 MJ. A sophisticated quench detection and protection system [17] is installed to dump this energy in a safe way if a quench occurs.

RF AND SYNCHRONIZATION

A 52 MHz system is used in HERA to accept the 2.2 m long bunches delivered from PETRA. The HERA frequency is not phase locked to that of PETRA during injection, a difference frequency of 1.3 kHz is necessary to make up for a small difference in orbit length in PETRA from the "smooth" value. The correct RF-phase at injection is found by a digital counter technique triggering the kickers at the right moment. The same procedure [18] is used between DESY3 and PETRA2. This "flying injection" could be adopted because synthesized RF-frequencies are used only. Also during the fast ramping of DESY 3 with a frequency ratio of 3 a quartz controlled synthesizer is preprogrammed [18]. This system worked well from the beginning and is extremely flexible. It is now being installed for the electron injection.

Bunch compression is obtained in HERA using another RF-system at 208 MHz with higher voltage [19]. It is turned on during the acceleration period.

STRAIGHT SECTIONS

In three of the four straight sections the counter rotating beams are colliding head on without crossing angle. The separation of the two beams on both sides of the interaction points is done by weak horizontal bending magnets. The protons are hardly affected whereas the electrons/positrons are deflected by 10 mrad. The first focussing quadrupoles for the protons are positioned after the separation 34 m apart from the interaction point. A pair of vertical bending magnets then brings the proton beam into its position 81 cm above the electron beam within the arc.

The weak bending magnets in front of the interaction point will cause severe background problems for the experiments due to the emitted synchrotron radiation. A set of absorbers to intercept the direct and the scattered radiation is foreseen. A reduction of 9 orders of magnitude of the number of photons with energies above 20 keV is necessary for the experiments to survive.

Normal conducting magnets were used for the protons in the straight sections in order to avoid the heavy thermal load on the cryogenic system by synchrotron radiation.

COMMISSIONING OF THE ELECTRON RING

First trials were made in August '88 to inject electrons into the newly assembled HERA ring. Only three days later electrons were stored for 20 minutes. This first 6 week period was mainly used to commission technical components.

A second run in September '89 focussed on the performance of the ring. Beam currents of 3 mA could be injected, accelerated to 27.5 GeV and stored with a lifetime of several hours. The maximum electron energy of 27.5 GeV was limited by the available RF voltage.

In May and June '91 a set of 12 four cell 500 MHz superconducting cavities assembled by pairs into 6 cryostats were installed. These cavities [20,21] were industrially produced from high purity niobium (RRR=300). At the design current of 58 mA the gradient is limited to 2.05 MV/m due to the 100 kW power rating of the input coupler. (New couplers for much higher power are now under test.) Without beam all cavities reached 5 MV/m. The design Q value of $2 \cdot 10^9$ could not be reached in all cases due to a Hydrogen precipitation on the Niobium surface.

In the same period a longitudinal and a transverse damping system similar to that tested in PETRA 2 was installed as well as the laser polarimeter needed to measure the electron spin polarization.

The following results were obtained during the last HERA-e commissioning in June 1991:

- The injection efficiency into HERA at 12 GeV was 93 %.
- The electron beam was ramped to 30.3 GeV with the superconducting cavities providing 37 MV or 1/4 of the required circumferential voltage. The superconducting

cavity system worked very reliably. The maximum gradient during this period was 4 MV/m (at a beam current of less than 5 mA), limited by the available klystron power.

- The maximum single bunch current was 2.49 mA nearly a factor of 10 above the design value.
- The maximum current in a multibunch mode without the feedback system was 6 mA in 30 bunches limited by radial instabilities. Feedback could be tested on single bunches only, where it reduced the betatron damping time by a factor of 50. We therefore expect to achieve the design current of 58 mA in 210 bunches.
- The polarimeter was commissioned and a series of measurements of the up/down asymmetry of backscattered laser light using a tungsten scintillator sandwich counter was made. A first transverse electron polarization of (8±1) % has been observed [22].
- The vertical dispersion after orbit corrections to 0.7 mm rms was 15 cm, corresponding to 5 % vertical coupling. This was compensated for the polarization measurements using large vertical orbit bumps.
- The dynamic acceptance was 9 π mm mrad, corresponding to 11.9 standard deviations at 35 GeV.

A pair of 60 m long magnetic rotators to turn the vertical spin axis into the longitudinal direction at an interaction point is prepared. Installation will only take place if more than 60 % polarization is observed.

COMMISSIONING OF THE PROTON RING

The first test run of the completed proton ring started on March 4 1991 and continued through April. After a 4 week checkout of the 400 power supplies and the quench protection system a 7 GeV positron beam was injected and used to adjust the timing of the beam position monitors. A positron bunch from PETRA could be obtained every second, but it takes 5 minutes to get the next 40 GeV proton bunch.

After switching to protons PETRA delivered single bunches with intensities varying between $1 \cdot 10^9$ to $3 \cdot 10^{10}$ particles. The normalised 2σ transverse emittance was about 15 π mm mrad in both planes in agreement with the design value; the observed bunch area of 0.1 eVs is 30 % less than design.

On April 14 the first proton beam was stored in HERA. The commissioning was greatly eased by the excellent performance of beam position monitors [23,24]. The tune measurement system [25] and the residual gas beam profile monitors [26] worked immediately. Fig. 5 shows a beam profile measured with the residual gas monitor.

The superconducting magnets were temperature- and current cycled to erase the persistent current sextupoles.

After correcting a few reversed quadrupole connections the measured amplitude functions were found to be in reasonable (20 %) agreement with calculation. Beam lifetimes of 30 min were obtained at the end of this run.

At the beginning of the second (and last) run starting in late August the persistent current multipoles were no longer suppressed.

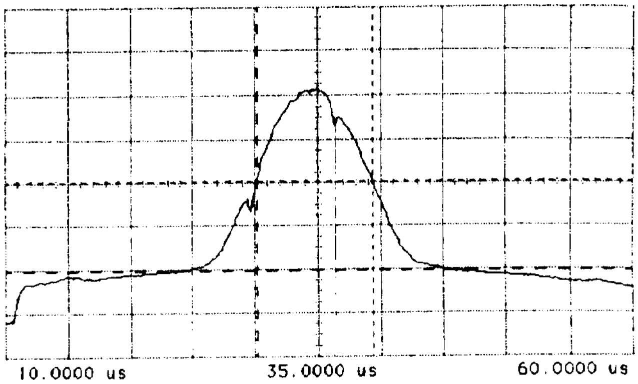

Fig. 5: Beam profile measured with the residual gas monitor. Full-width at half height is 13.8 mm.

After compensation of the persistent current multipoles using the correction coils wound on the beam pipe and adjusting the working point to $Q_x = 31.29$, $Q_y = 32.29$ a beam lifetime of more than 3 hours was obtained at 40 GeV.

The injection efficiency was nearly 100 %. The geometric acceptance was 3..4 (6) π mm mrad, and the dynamic acceptance was about 1.5 (3) π mm mrad. In ( ) are the design values. The rms orbit deviations were about 3 mm in both planes. We expect that the acceptance will be improved by better orbit correction and improved tuning of the multipole correctors.

The 2 m long PETRA bunches were captured in 52 MHz buckets. The beamloading in the four 208 MHz cavities was compensated to zero with a feedback system and pair wise counterphasing of the cavities. When the 208 MHz voltage was raised the bunch could be compressed and captured in the shorter bucket. But all acceleration and collision tests were made with the 52 MHz voltage only.

The next step was to ramp and store the beam at collision energies. During this running period the current in the superconducting main dipoles was limited to 3000 A corresponding to 480 GeV. This was done to protect the magnets against a voltage overshoot to ground during a fast dump of the energy stored in the magnets. Meanwhile a better damping of the magnet circuit avoids this problem.

The acceleration cycle proceeds in two steps: the beam is injected at 40 GeV and then accelerated to 300 GeV. At 300 GeV the beam optics is changed from injection to luminosity conditions and then the beam is accelerated to 480 GeV. During the transition from injection to luminosity conditions the maximum β-functions change from 270 m to 1000 m.

A small beam loss and emittance growth was observed only during the early part of the ramp presumably due to orbit and chromaticity changes [27] which require improved control. The life time of the protons at 480 GeV was about

100 hours.

The first HERA proton ring commissioning runs were rather successful. Both the superconducting magnet system and the helium refrigeration system were reliable and caused little downtime. The quench protection system worked very reliably, only very few spurious quenches occurred. The beam vacuum [28] in the cold arcs was better than 10^{-12} mbar. In the warm straight section East, which had been baked out in situ at 250 C, the vacuum was a few 10^{-10} mbar. In the remaining three straight sections the vacuum was 10^{-8} mbar. These sections are being baked out now. The beam abort system [29] did not fire spontaneously and worked every time needed.

COLLIDING BEAMS

The electron ring was turned on again in early October and both rings operated simultaneously for the first time. Note that the magnets near to the interaction points are common to both rings.

The first collisions were obtained on October 19th with 12 GeV electrons against 480 GeV protons. The two counter rotating bunches were centred transversely using beam position monitors located ±7 m from the interaction point. Then the electron and proton RF frequencies were locked and the phase adjusted while the passage of the two bunches was observed in the third interaction region. An increase in counting rate of the luminosity monitor was observed immediately. During the collision period the proton lifetime decreased from 72 hours to less than one hour.

The luminosity is measured using the reaction $e+p->e+\gamma+p$ with the electron and photon detected in coincidence [30,31]. The arrangement of the luminosity monitors is shown in fig.6. The electron photon coincidence rate measured by the ZEUS luminosity monitor during the collisions of 26 GeV electrons and 480 GeV protons is plotted in fig. 7 [32].

A new method was probed to find the optimum beam alignment at the interaction points for collision [33]. The electron beam is excited very weakly by transverse kickers near the betatron frequencies of the protons. A central beam collision results in the largest signal on the Schottky monitor of the protons. Even when the beams are missing each other by some standard deviations the signal is clearly visible and may be used for automatic alignment.

Until the end of the run on December 2nd the following results were achieved:

- The colliding electron bunch intensity was near to the design value of $3 \cdot 10^{10}$ particles/bunch.
- The intensity of the proton bunch was 20 % of the design value of $1 \cdot 10^{11}$ protons/bunch
- The peak luminosity measured in both interaction regions at the same time was $3 \cdot 10^{28} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. This was achieved with 10 bunches in each direction but with reduced current per bunch.

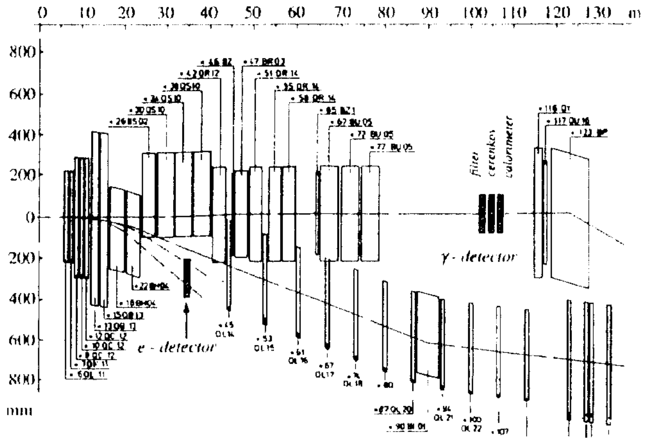

Fig. 6: The layout of the luminosity detectors designed to monitor the reaction $e+p \rightarrow e+\gamma+p$. Note the different scale along and transverse to the beam.

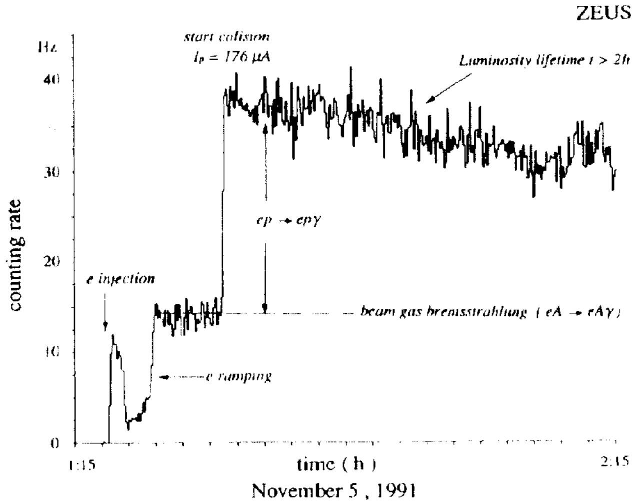

Fig. 7: The electron-photon coincidence rate measured with the ZEUS detector as a function of time.

- The specific luminosity agreed with that calculated from current and profile measurements.
- The maximum beam beam tune shift calculated for the protons was 0.001/0.0005 in x and y direction respectively, very close to the values assumed in the proposal.
- For the electrons tune shifts of 0.003 in both directions were obtained.
- The lifetime of the protons during collision strongly depends on the tune, on the good matching of the beam sizes at the interaction point and on the exact alignment of the beams with respect to each other.
- Under these conditions the proton life time was about 4 hours.
- The beam orbits were very reproducible. The same setting of correction elements could be used for many collision

runs nearly without additional tuning.

First measurements of the hadron background caused by the proton beam gave negligible rates without beam beam collisions. With collisions the background increased significantly. One pair of horizontal and vertical collimators in the straight section West reduced the background rate by a factor of 5 to 10 in accordance with simulations. A second and third pair are now installed at such a distance from the first as to remove scattered protons. Another factor of five reduction per pair is expected. If one takes this reduction into account and scales the background linearly up to the design proton current, then the trigger system of the experiments should be able to handle the hadronic background rate.

All these results are very preliminary and were achieved within only a few collision runs. No systematic attempt was made to look for better tunes or to correct the orbit, the chromaticity or higher multipoles.

NEXT STEPS

Between December 1991 and March 1992 the experiments H1 and ZEUS are being moved into their final position around the interaction points. The beams will be switched on again in April 1992.

From the beginning the machine time will be shared between machine R&D and the experiments.

The protons should be accelerated to their full energy of 820 GeV. The filling of more than 10 bunches (up to 210) has to be tested in both machines. Increased proton intensity is required which is mainly a function of the performance of the preaccelerators.

CONCLUSIONS

No principle problems arise during the collisions of electrons and protons.

The persistent current multipoles are well compensated by the correction system and a ratio of 20 between injection and final proton energy does not degrade the machine performance at the injection level.

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