HERA UPGRADE PLANS

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Abstract

HERA is a 6.3 km long $p/e^{+/-}$ double ring collider located at DESY (Hamburg). The proton and the electron(positron) beams are accelerated up to 820 and 27.5 GeV respectively and collide head-on at the interaction points (IP's) North and South, where the experiments H1 and ZEUS are located. The machine has been in operation since 1992 for these experiments. A third experiment, HERMES, using the longitudinally polarized $e^{+/-}$ beam traversing a gas target, started data taking in 1995. The HERA-B collaboration is currently making test runs; this experiment will use the proton beam halo for CP violation studies. Now that the machine has nearly reached design performance with very satisfying beam quality, a further increase of the collider luminosity achieved by reducing the transverse beam size at the IP's is being prepared. For this purpose it is planned to reduce the $\beta^*_{x,z}$ of both rings. As a consequence, some machine magnets must be moved into the experimental regions and the anti-solenoids, currently used for compensating the effects of the H1 and ZEUS solenoids, must be removed. Moreover, in order to reduce the $e^{+/-}$ beam emittance, it is planned to increase the horizontal phase advance in the FODO cells of the $e^{+/-}$ ring from the present 60^0.
This paper summarizes the main issues for this concept.

1 INTRODUCTION

Over the last few years the luminosity delivered by HERA has been steadily increasing, as sketched in Fig. 1. In 1997 the peak luminosity reached values up to 1.4×10^{31} cm^{-2}s^{-1}, very close to the design value. Although the vertical beam-beam tune shift experienced by the $e^{+/-}$ has reached values of 0.035, it has been possible to deliver routinely longitudinal polarization above 50 % to the HERMES experiment.

After a year long workshop between 1995 and 1996 [1] physicists concluded that an integrated luminosity of the order of 1 fb^{-1} in 5 years running time would open the possibility of many exciting measurements in the fields of the EW and strong interaction.

Since 1996 a group of HERA machine physicists and members of the H1 and ZEUS collaborations has looked into the feasibility of a HERA luminosity upgrade. The solution finally adopted will be reviewed in this paper. An exhaustive description of the project may be found in [2].

2 HERA STATUS

In 1997 it was possible to get up to 105 mA of protons in 180 bunches into collision, namely about 76 % of the design current per bunch. Serious limitations to the storable current did not show up, the maximum current being actually limited by the losses during the machine-to-machine transfers.

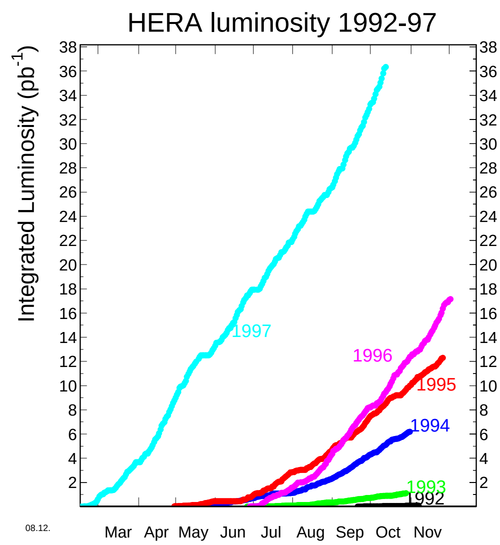

Figure 1: The integrated luminosity delivered by HERA to ZEUS versus time.

With electron currents above 20 mA sudden drops of the e^- lifetime have been observed [1] [3]. Therefore in the last three years HERA has been operated mainly with positrons. The maximum stored positron current is limited to about 45 mA (80 % of the design current per bunch) by the RF power. Improvements of the RF system are being steadily undertaken and a new rf station is being installed.

The $\beta^*_{x,z}$ values have been decreased leading to a reduction of the beam size at the IP's by about a factor of 2.

The operational efficiency has been steadily improved over the years and is now above 40 %.

There is still space for improvements. However it is clear that in order to meet the wishes of the experimenters it is also necessary to reduce drastically the size of both beams at the IP's.

[1] The integrated ion sputter pumps in the main dipoles have now been replaced with NEG pumps; it is expected that this will solve the e^- beam lifetime problems.

3 MACHINE DESIGN FOR THE LUMINOSITY UPGRADE

3.1 Main Parameters

For the design of the Luminosity Upgrade it has been assumed that the beam currents will not exceed their original design values.

There is some interest in running the proton ring at energies above the current 820 GeV. Without loss of luminosity it should be safe to run up to 920 GeV.

The $e^{+/-}$ energy is limited by the available RF power. The HERA Upgrade design is scalable to 30 GeV, although in practice we expect that we must operate below 28.5 GeV in order to get the design current of 58 mA.

During the years of HERA operation we have learned that to have good conditions during luminosity operation it is essential that the sizes of the two beams are matched; this is understood as a minimization of non-linearities in the beam-beam interaction. The total $e^{+/-}$ current, I_e, is limited by the RF power and the maximum proton brightness N_p/ϵ_N (ϵ_N being the normalized proton emittance) is limited by space charge effects in DESY III. By writing the luminosity in terms of such parameters:

$$L = \frac{\gamma_p}{4\pi e} \frac{I_e}{\sqrt{\beta_x^{*,p}\beta_z^{*,p}}} \frac{N_p}{\epsilon_N}, \qquad \text{with } \sigma_{x,z}^p = \sigma_{x,z}^e$$

it is clear that the luminosity may be increased only by decreasing the proton $\beta_{x,z}^*$. This implies that the quadrupoles must be placed as close as possible to the IP, that the two beams must be separated as soon as possible and that synchrotron radiation is produced in the experiment region.

In fact the lowest value of β^* is limited by aperture requirements and by the need to keep the chromaticity budget as small as possible. In this regard it is of course convenient to focus the beams as close as possible to the IP. Therefore it has been decided to remove the anti-solenoids and to put the first $e^{+/-}$ magnets already inside the detector (their effect on the more energetic proton beam is about 30 times smaller).

Since the head-on collision scheme is also maintained in the new design, the separation of the two beams is achieved magnetically by deflecting the $e^{+/-}$ beam. The bending radius must be as large as possible to minimize synchrotron radiation generation in the detectors. With an overall deflection of 8.8 mrad of the $e^{+/-}$ beam, the separation at 11 m from the IP is about 60 mm, sufficient to accommodate the first of the two proton septum quadrupoles. The maximum tolerable proton β function values at this location determines the minimum value of $\beta_{x,z}^{*,p}$.

The smallest size of the longer of the two beams, namely the vertical size of the protons (currently $\sigma_l^p \geq 10$ cm) is finally limited by the so called “hourglass” effect.

A consistent solution fulfilling all constraints and delivering an important luminosity gain has been worked out. The resulting parameters are summarized in Table 1

parameter	e-beam	p-beam
E (GeV)	30	820
# of bunches (tot/coll)	189/174	180/174
I (mA)	58	140
ϵ_x (nm rad)	22	5.7
ϵ_z/ϵ_x	0.18	1
β_x^* (m)	0.63	2.45
β_z^* (m)	0.26	0.18
σ_x^*, σ_z^* (μm)	118, 32	118, 32
$\Delta\nu_{x,z}$/IP	.027, .041	.0017, .0005
L (cm^{-2}s^{-1})	7.00×10^{31}	
L_s (cm^{-2}s^{-1}mA^{-2})	1.56×10^{30}	
improvement w.r.t. design	4.7	

Table 1: Parameters of Upgraded HERA

The proton beam-beam horizontal tune shift, $\Delta\nu_x^p$, is higher then the current one, but is still far from the limits found at the SPS and TEVATRON. The $e^{+/-}$ beam-beam vertical tune shift, $\Delta\nu_x^e$, is similar to the largest value achieved at HERA.

4 NEW IR LAYOUT

The right side of the new IR layout is sketched in Fig. 2.

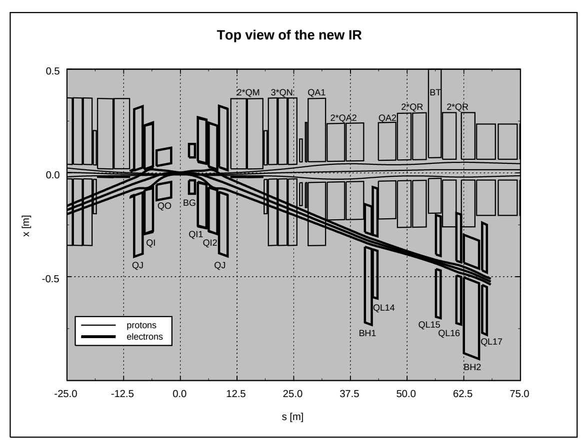

Figure 2: IR layout (right side)

Both beams go through the first four $e^{+/-}$ magnets: the superconducting BG dipole and three quadrupoles of type QI. The dipole will be shifted outwards by 27 mm to let synchrotron radiation to go through. The first QI magnet will be shifted in order to create a dipole component too. The first proton magnet, the QM, is placed at about 11 m and is followed by a second QM, three QN type quadrupoles and two QA type quadrupoles. These proton magnets are specially designed to provide space for the $e^{+/-}$ beam and for the synchrotron radiation fan. Starting from about 55 m the two rings are completely separated. For space reasons, before this point no further focusing of the $e^{+/-}$ beam is possible. The magnets which follow are all of standard HERA type.

The layout on the left side is slightly different, the BG and the first QI being replaced by a long and slim superconducting magnet (QO) which fits into the small space available inside the H1 forward calorimeter. For practical reasons it is not possible to install such a magnet on the right side also. This leads to a somewhat unpleasant asymmetry of the lattice layout. The QO magnet provides a dipole as well as a quadrupole component on its axis. Moreover it will be shifted by about 6.8 mm from the design orbit (the detector axis, at the IP's) and in order to minimize its aperture (it is 3.2 m long) it will be radially tilted by -4 mrad. For the same reason the first QI on the right side will be tilted too.

An important feature of HERA is the possibility of running both with positrons or electrons. The effect of the $e^{+/-}$ ring magnets on the protons is small but not negligible. When switching from one kind of particle to the other, the proton optics must be slightly readjusted. This will be the case also with the new design. Due to lack of space, however, the proton orbit change will no longer be locally compensated by dedicated dipoles. The idea is to shift some of the machine components, and thus the IP, to follow the changed proton orbit.

5 PROTON RING

Fig. 3 shows the Twiss functions near the new IR for luminosity operation of the proton ring.

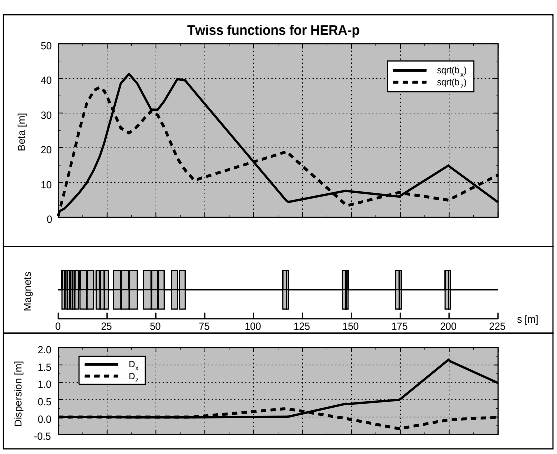

Figure 3: Proton ring Twiss functions at the new IP.

It is worth noting that the current 12.5 σ aperture limit has been maintained in the new design also. As at present, slightly different optics are needed depending on whether the machine is operating with e^- or e^+.

6 ELECTRON/POSITRON RING

6.1 Optics

The impact on the $e^{+/-}$ ring is quite severe. In order to relax the conditions on $\beta_x^{*,e}$ a decrease of the $e^{+/-}$ beam emittance by means of a $90^0/60^0$ FODO lattice has been adopted. It has been assumed that two spin rotator pairs similar to those already installed in the East [4], will be introduced in North and South. The optics has been designed with the computer code SPINOR [5] in order to get first order transparency for the spin motion (spin matching) as well as the usual optical requirements. Fig. 4 shows the $e^{+/-}$ Twiss functions along the new IR for luminosity operation. One of the spin rotators is located in the region between 130 m and 200 m.

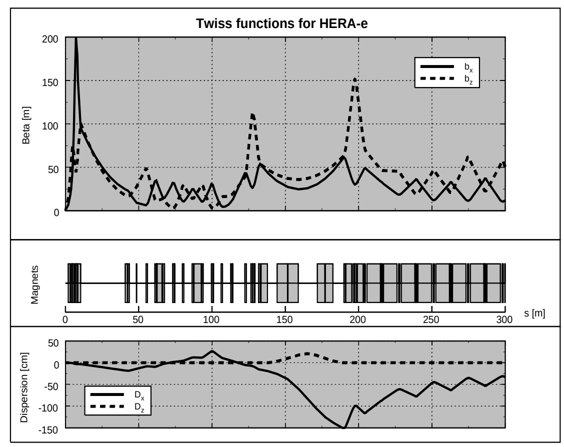

Figure 4: $e^{+/-}$ ring Twiss functions up to the arc.

6.2 Chromaticity Correction and Dynamic Aperture

The increase of the focusing strength in the FODO cells increases the natural chromaticity and the lower horizontal dispersion forces the use of strong sextupoles to compensate it. These sextupoles may introduce large non-linear perturbations. A scheme must be worked out allowing to correct the linear chromaticity and the first order order chromatic wave, keeping the non-linear effects as small as possible. Several correction schemes have been considered [6, 7]; it is expected that the dynamic aperture will be smaller then in the current design, but still sufficient.

6.3 Impact on $e^{+/-}$ Polarization

HERA-e is the only high energy ring delivering longitudinal spin polarization. The planned increase of the luminosity must not spoil the polarization that can be delivered to HERMES and also to H1 and ZEUS.

The main concerns are the effects of the overlap of the experiment solenoid fields with the vertical dipole fields of the machine magnets. With this configuration the solenoids produce a vertical orbit distortion in addition to the other usual effects. We have concentrated our attention mainly on the H1 solenoid which has a higher integrated field and is longer then the ZEUS one and is longitudinally off center with respect to the interaction point.

At present anti-solenoids are compensating for the betatron coupling and for the strong distortion of the periodic solution, $\hat{n}_0$, to the T–BMT [8] equation, caused by the experimental solenoids (about 120 mrad in the H1 solenoid).

In the new design the QO and BG magnets will be equipped with windings producing a skew quadrupole and a horizontal dipole field. The skew quadrupole windings together with dedicated skew quadrupoles will be used for compensating the betatron coupling, whereas the dipolar windings will allow a local correction of the vertical orbit. The maximum vertical orbit excursion will be below 0.13 mm.

If the spin rotators are operating, the nominal $\hat{n}_0$ is longitudinal at the IP's, but we must correct for the fact that it is not yet perfectly longitudinal when entering the solenoid and that the middle of the solenoid is shifted longitudinally with respect to the IP. The resulting distortion (about 10 mrad in the H1 solenoid, after correcting the orbit) may be corrected to less than 1 mrad by slightly different settings of the rotator vertical bending magnets on the left and on the right side of the IP.

In order to get a first estimate of the polarization we have used SLIM/SLICK [9] and modeled the overlapping fields as an interleaved sequence of thin "combined function magnet–vertical corrector–solenoid" slices. In spite of the crudity of this model, spin–orbit trajectories computed with this approach are in satisfactory agreement with the results of a simple code [10] solving the equations of motion for orbit and spin in a three-dimensional field. Work on a better representation of the effect of the overlapping fields using symplectic maps obtained from integration is in progress [11].

In spin matching the optics, however, we have ignored, as a first attempt, the presence of the experimental solenoids. Then linear calculations (SLIM) show that when the H1 solenoid is switched on the maximum polarization that can be achieved for the ideal machine is reduced from 79 % to about 58 %. By correcting coupling, orbit and $\hat{n}_0$ axis tilt the maximum polarization reaches about 73 %. This should improve after spin matching with inclusion of the solenoids.

It is worth noting that the high $\Delta\nu_z^e$ will require a very careful tuning of the machine for polarization during luminosity operation.

7 NEW MAGNET DESIGN

7.1 Normal Conducting Magnets

Six new types of normal conducting magnets will be needed. Their design is quite challenging as gradients up to 30 T/m with good field quality ($\Delta B/B \leq 10^{-4}$ at r =25 mm), large aperture and small size are required. These magnets will be built at the Efremov Institute (St. Petersburg).

The QI magnet [12] is 1.88 m long and has a pole radius of 37 mm. In order to fit into the experiments this magnet must have a small size (width 52 cm). Therefore to provide up to 28 T/m the current density in the coils must be large. A gap between the coils on the outer side allows synchrotron radiation go through.

The QJ magnet [12] is 1.88 m long, with a pole radius of 50 mm, and should provide up to 18 T/m. A gap between the coils on the outer side allows synchrotron radiation to go through.

The QM septum quadrupole [13] is a 3.4 m long half quadrupole with mirror plate. The maximum gradient is 25 T/m. The pole radius is 37 mm. The plate has a triangular cut-out for providing a (field free) space for the $e^{+/-}$ beam pipe. This cut compromises the symmetry of the design and thus the field quality. However it has been found that a pair of correction windings around the mirror plate would reestablish good field quality. Between the outer coils the magnet is open to let the synchrotron radiation go through.

The QN septum quadrupole [14] is 1.95 m long providing gradients up to 30 T/m. The pole radius is 35 mm. The magnet is open on the outer and inner sides providing space for synchrotron radiation and $e^{+/-}$ beam pipes respectively. As a consequence this magnet is quite wide. As the space available for the coil between the two beams is only of 50 mm, the coils are small and the current density high. The design minimizes the field seen by the $e^{+/-}$ beam, the residual fields being shielded by a plate.

The QA1 quadrupole is a "relaxed" version of the QN one. The QA2 quadrupole has only one pipe, but with small return yoke in order to keep its width as small as possible. The required gradient is 26 T/m.

7.2 Superconducting Magnets

Only superconducting magnets can achieve the required field with large aperture (for the synchrotron radiation) and fit into the small space available inside the detectors (down to 19 cm diameter at the H1 FDET).

The superconducting coil for both BG and QO [15] magnets consists of three quadrupole layers and one dipole layer. They are equipped with single layer correction coils to make a skew dipole and a skew quadrupole component. The coils will be wound on their support by using a computer controlled 3-dimensional ultrasonic bonding device.

The QO is 3.2 m long and has an aperture radius of 45 mm, whereas the BG is 1.3 m long with an inner radius of 55 mm. They both provide a vertical dipole field of about 0.2 T and gradients up to 14 T/m.

The superconducting quadrupoles will be built at the Brookhaven National Laboratory where tests on a prototype superconducting coil have already been performed. It turned out that eddy currents induced during ramping are negligible and that the field quality is satisfactory.

8 SYNCHROTRON RADIATION AND BACKGROUND IN THE IR

The fact that the proton and $e^{+/-}$ beams must be separated near to the experiments leads to increased synchrotron radiation (SR) generation in the experiments with respect to the current situation. At 30 GeV with 58 mA the total radiated power will be 26 kW for each IR. The critical energy is 150 keV. It is not convenient to absorb this radiation too near to the IP because of the unavoidable back reflected radiation and because of the large out-gassing of the hit surfaces which would raise the local pressure and cause more background in the form of gas bremsstrahlung.

The solution adopted consists in providing sufficient aperture to allow the SR to pass through up to 11 m right of the IP and then allowing it to escape along a special "exit" pipe where it will be absorbed by the main absorber at about 26 m. A second absorber at 11 m absorbs the part of the radiation fan which would otherwise hit the joint between the beam pipes.

Secondary absorbers will have the task of protecting the experiments from the radiation reflected back by the main ones and from the SR generated upstream of the IP by an accidentally off-centered $e^{+/-}$ beam.

The radiation reflected back to the IP by the main absorbers is minimized by choosing very small incidence angles and by giving the surfaces an anti-reflective coating. The back-reflected power should be 0.3 $\%$.

Under these conditions the SR background appears to be tolerable.

A second source of background is particles of the $e^{+/-}$ beam interacting with the rest gas upstream of the IP and losing up to 50 $\%$ of their energy via bremsstrahlung. Simulations show that with the new IR design a large fraction of these would hit the beam pipe inside the detector creating serious problems to the first level of trigger. Thus a kind of "chicane" has been introduced for getting rid of a proportion of these particles, the remainder being absorbed by a couple of collimators. In addition, an improvement of the vacuum in a short region upstream of the experiments would reduce this background to an acceptable level.

9 IMPACT ON THE EXPERIMENT COMPONENTS

The effect of the stray field of the QO and BG magnets on the inner photo-multipliers will be reduced by a shield surrounding the cryostat. Additional shielding of the photo-multipliers and/or the use of photo-multipliers less sensitive to the magnetic field is also possible.

The performance of the various detector components with the new IR design has been studied with Monte Carlo simulations and found satisfactory; only an energy excess is observed in the Forward Calorimeter for low Q^2 events due to particle showering in the machine magnets.

The Leading Proton Spectrometer stations can also be accommodated in the new layout.

The main concern is the luminosity monitors. Improvements of the detectors must be undertaken in order to get a measurement precision better then 1 $\%$ as at present.

10 SCHEDULE

The feasibility studies for the increase of the HERA luminosity began at the end of 1996. The main aspects of the new IR design were fixed in the summer of 1997. The approval for the project came in December 1997. The design and construction of the magnets and of the vacuum components is in progress. The project is supposed to be realized in the year 2000.

11 ACKNOWLEDGMENTS

The author thanks all colleagues who kindly provided her with pictures and explanations and in particular F. Willeke for his guidance and D. P. Barber for carefully reading the manuscript.

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