First Experience with Colliding Electron-Proton Beams in HERA

R. Brinkmann and F. Willeke
Deutsches Elektronen Synchrotron
Notkestr.85, 2000Hamburg 52, Germany

Abstract

We report on first experience with colliding electron and proton beams in HERA (see also [2]). In 1992, the first year of operation, HERA has delivered some $60(nb)^{-1}$ of e-p Luminosity to the experiments H1 and ZEUS. The beam energies amounted to $26GeV$ and $820GeV$. A maximum luminosity of $2.2 \cdot 10^{29} cm^{-2}s^{-1}$ has been achieved by colliding a train of nine electron bunches against nine proton bunches. A complete collection of data is contained in reference[1]. The beams could be brought into and held in collision without problems. The lifetime of the proton beam in collision is as long as $50h$. This requires both careful matching of the electron and proton beam cross sections and also that the two orbits coincide within $\simeq 0.2\sigma$ beam size at the interaction point. The proton beam suffered a beam-beam tune shift of up to $\Delta Q_x \simeq 0.0018$. This is close to the limit which was assumed in the design of HERA. Nonetheless, there is only little degradation in the proton beam quality in collision. Under these conditions, the proton beam fills could be stored and be made available for collision for some $24h$ in HERA.

I. Introduction

On October 20, 1991, a $480GeV$ proton beam and a $12GeV$ electron beam have been collided for the first time in the double storage ring HERA. Good colliding beam conditions had been accomplished in the last weeks of 1991 so that the the machine could be made available for a luminosity production run in 1992. Operations started with a test run during which the procedures to inject into the machine, to accelerate the beams to full energy and to bring them into collision were established and set up for routine operation. The two experiments ZEUS and H1 were able to start data taking almost immediately after the start up on May 31. This test run was followed by a 7-week production run in the fall in which the experiments collected approximately $53(nb)^{-1}$.

There were a number of concerns during the design of the double ring electron-proton collider. Above all was the question about the stability of the proton beam when colliding with a high intensity electron beam. Other interesting questions were also how difficult is it be to bring the two beams into collision, and how to maintain stable operation during collision.

Meanwhile, answers to these questions are available which are discussed below.

The scope of this report will be as follows:

In the first section we will summarize the parameters and the results of the 1992 luminosity run.

In the second section we will discuss practical aspects of electron proton collision such as beam finding algorithms, stability and reproducibility of collision orbits.

Finally we will analyse the proton beam stability. We discuss the relevant parameters and we will make comparisons with predictions.

We will conclude with a short outlook on 1993 beam-beam operation.

II. Overview of the 1992 Luminosity Operation

The luminosity operation in the fall of 1992 included 80 colliding beam runs. $820GeV$ protons collided with $26.6GeV$ electrons. Each run lasted on average $\simeq 5h$. A total luminosity of $53(nb)^{-1}$ has been accquired by each of the two experiments. The operation was limited to nine colliding bunches. A tenth proton and electron bunch respectively were also present to allow for background discrimination. The reason for the restriction to a relatively small number of colliding bunches (design value is 210) was originally to ease the start up of the experiment especially in view of the complex trigger system. Later, however, it turned out that the beam intensity of the electrons was limited to $\simeq 3mA$ due to a breakdown of the beam lifetime. This problem was only resolved by the end of the year by exchanging a small section of beam pipe.

The bunch intensity of the proton beam was limited by the preaccelerators. In 1992, bunches with up to $3 \cdot 10^{10}$ protons have been delivered by PETRA, this is about 30% of the design goal.

For other parameters it could be demonstrated that the design goals can be reached.

The transverse emittance of the proton beam suffered in some cases from a horizontal excitation which increased the transverse beam size. This is why average and best achieved values of the proton emittance differ by a factor of more than two. The values of the β-function have been increased intentionally for the electron beam whereas they have been squeezed beyond the design values for the proton beam. The reason is to obtain a better match of the beam cross sections, which turned out to be crucial for the proton beam stability. This will be discussed below.

The specific luminosity which was obtained with these parameters exceeded in some cases the design goal. In all cases, the specific luminosity as measured by the luminosity monitor (see below) compares well with the values calculated from the measured beam dimensions. The stability of operations is reflected in the fact that the specific luminosity remained nearly constant over a whole luminosity run of $5h$. This indicates that there were no difficulties to bring the beams into collision and to maintain good con-

0-7803-1203-1/93$03.00 © 1993 IEEE

ditions for collision.
Table 1 reviews the beam parameters of the 1992 luminosity run.

Table 1: Parameters of the 1992 Luminosity Run	Mean	Best	Goal
Beam Energy/GeV			
Electrons	26.6	26.6	30.
Protons	820	820	820
Number of Bunches	9	9	210
N_e/Bunch $[10^{10}]$	3.3	4.3	3.6
N_p/Bunch $[10^{10}]$	2.5	3.2	10
Emittance			
$\varepsilon_{x,p}/\pi mrmm$	0.015	0.0062	0.007
$\varepsilon_{y,p}/\pi mrmm$	0.015	0.0046	0.007
$\varepsilon_{x,e}/\pi mrmm$	0.039	0.039	0.039
$\varepsilon_{y,e}/\pi mrmm$	0.002	0.002	0.002
β-Function Values at IP			
$\beta_{x,p}/m$	7.0	7.0	10.0
$\beta_{y,p}/m$	0.7	0.7	1.0
$\beta_{x,e}/m$	2.2	2.2	2.0
$\beta_{y,e}/m$	1.4	1.4	0.7
Beam Size at IP			
$\sigma_{x,p}/mm$	0.324	0.210	0.265
$\sigma_{y,p}/mm$	0.102	0.052	0.084
$\sigma_{x,e}/mm$	0.29	0.29	0.27
$\sigma_{y,e}/mm$	0.053	0.053	0.036
Beam-Beam Tuneshift/IP			
$\Delta Q_{x,p}$	0.0007	0.0009	0.0013
$\Delta Q_{y,p}$	0.0004	0.0005	0.0010
$\Delta Q_{x,e}$	0.003	0.011	0.018
$\Delta Q_{y,e}$	0.007	0.020	0.020
Luminosity			
per Bunch $[10^{28}cm^{-2}s^{-1}]$	1.2	2.4	7.14
Spec. $[10^{29}cm^{-2}s^{-1}mA^{-2}]$	2.3	4.4	3.4

III. Operational Aspects of e-p Collisions

Routine operation could be established after a few weeks of colliding beam operation. The following played an important role in this successful start up

- Beam Position Pickups Available Close ($7m$) to the IP
- Availability of Fast Luminosity Monitoring
- Reproducibility of Collision Orbits after a Magnetic Cycle

Pairs of capacitive pickups are located on both sides of the interaction points. The position of the two beams is measured independently (one after the other). Due to the reproducibility of the beam orbits within $0.1mm$ for a particular setting of the magnets, this measurement allows us to bring the two beams as close as $1-2\sigma$ of the beam cross section. This can be repeated for many magnetic cycles before a new set up becomes necessary. The orbit of the protons need some $120min$ to become stable after thermal equilibrium is reached in the normal conducting magnets. The fine steering, to obtain complete overlap between the beams, is performed by observing the rates from the luminosity monitors. This device detects Bremsstrahlung emitted by electrons scattered at the protons. The off-energy electron is detected in coincidence. Beam-gas Bremsstrahlung is discriminated by the use of a non-colliding electron bunch (see also [3]). Every $30sec$ these monitors provide a luminosity value with a precision of $\simeq 4\%$ (for luminosities in the range of $10^{29}cm^{-2}s^{-1}$). Optimum collision orbits are found quickly ($20min$) by horizontal and vertical scans using closed orbit bumps. The life time of the proton beam usually drops from $50h$ to $1-5$ hours during this scan. A few percent of beam loss is taken into account. In case the beams are separated by several σ, finding the collision orbits was eased by observing and maximising the betatron frequency signal from one beam in the transverse spectrum of the other beam. This becomes a good collision monitor if the excitation signal for one beam is used as a reference for the lock-in amplifier of the beam signal of the other beam [5]. Due to the good orbit reproducibility this more sophisticated method was only rarely used in routine operation. During a colliding beam run, the beam orbits drift only very slightly and slowly. Manual corrections from time to time turned out to be adequate. This behaviour is expected from estimates of diffusive ground motion which predicts a separation of 1σ after $10h$. (using the ATL-law [6] with $<\Delta y^2>= A\cdot T\cdot L$, where $A = 10^{-4}\mu m^2 s^{-1} m^{-1}$, T is the time and L the value for a β-tron wavelength in HERA). Experience shows that dynamic beam separations are not important for HERA. This is in agreement with earlier investigations [4] which predicted a separation of only 0.1σ due to magnet vibrations, the most prominent contribution.

IV. Stability of the Proton Beam

The crucial issue in e-p interaction is the stability of the proton beam in collision. Due to the lengthy cycling, injection and ramp procedure of the proton machine (minimum turn around time is $60min$) proton beam lifetimes of more than 20h are required. Proton lifetime is also correlated with the background picked up by the experiments. and which becomes a problem if the lifetime drops below this number.
Necessary conditions for good proton beam lifetime in collision are to keep the tunes in a narrow window of $\Delta Q_{x,y} \leq 0.005$ at the working point of $Q_x \simeq Q_y - 1 = 31.295$ to stay clear from the nearby $7-th$ order and $10-th$ order resonances at 31.286 and 31.3 respectively. Besides a well corrected orbit and a compensated chromaticity ($\xi x, y \simeq +1$) it turned out to be important to compensate the width κ of the coupling resonance $Q_x - Q_y = 1$ to about $\kappa \leq 0.005$ in order to place the working point close to the main diagonal in the tune diagram.
The most important parameter for achieving high proton beam stability in collision, however, was found in the ratio of proton and electron beam sizes.
If the electron beam cross section is considerably smaller than the proton beam size, the proton beam life time may

drop by two orders of magnitude (from $100h$ to $1h$) for beam-beam tune shift values as moderate as $\Delta Q = 0.001$. Such effects have been observed earlier in the $Sp\bar{p}S$ collider [8]. In HERA, the beam optics has been modified in several steps. At the cost of increased beam-beam tune shift for the electron beam, the β-function values of the electron beam at the IP have been increased by almost a factor of two and the ones of the proton beam have been reduced by 30%. At each step, considerable improvement of the proton beam lifetime was achieved which is illustrated in Figure 1.

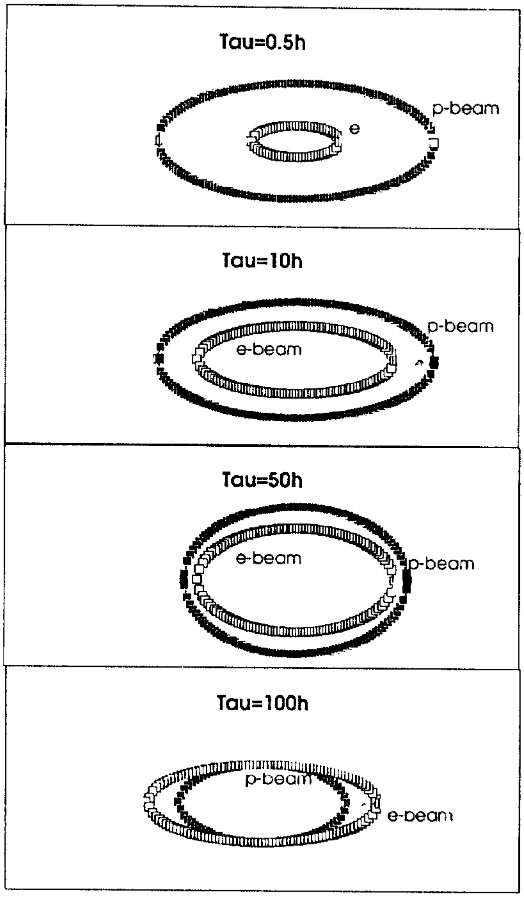

Figure 1: p-Beam Lifetime for different e/p Beam Cross Sections, Beam-Beam Tuneshifts $\Delta Q_{x,y} \simeq 0.0015$; from up to down:
$\sigma_{px/py/ex/ey} = 0.41/0.12/0.13/0.033mm \rightarrow \tau_p = 0.5h$
$\sigma_{px/py/ex/ey} = 0.41/0.12/0.29/0.07mm \rightarrow \tau_p = 10h$
$\sigma_{px/py/ex/ey} = 0.33/0.10/0.29/0.070mm \rightarrow \tau_p = 50h$
$\sigma_{px/py/ex/ey} = 0.21/0.05/0.29/0.053mm \rightarrow \tau_p = 100h$

Attempts have been made to understand this behaviour. Emittance growth rates have been calculated for protons colliding with an electron beam in HERA[9]. A tune modulation of 10^{-3} (which is somewhat stronger than expected from magnet power supply ripple) leads to strong threshold-like enhancement of emittance growth for particles with oscillation amplitudes larger than two standard deviations of the electron beam cross section.
Simulations of collision of protons with a flat electron beam ($\sigma_{y,p} = 2.75 \times \sigma_{y,e}$) have been performed which include oscillatory as well as random tune changes [7]. The result is also a rather strong emittance growth for protons with amplitudes larger than the electron beam size. This analysis at least qualitatively explains, what is observed in e-p collision.

Another important ingredient of good operating conditions is that the two beams are well centered with respect to each other at the interaction point. We estimate the critical value for transverse beam separation to be in the order of 0.2σ which corresponds to about $(10-20)\mu m$. For larger values we observe reduced proton beam lifetime. This is explained with the enlargement of the width of the nearby $7-th$ order resonance. An estimate of the maximum tolerable separation of the emittance growth threshold for large amplitude protons ($8\sigma_e$) on the 7th order resonance results in a separation of only $0.1\sigma_e$ (assuming a round electron beam and a $50Hz$ tune modulation with a depth of 0.001). Due to this effect, the process of bringing the beams into collision is critical and delicate. However, beam loss and emittance growth can usually be avoided by careful adjustment of the tunes. The optimization procedure should not take more than about $20min$ which was usually the case.

V. Conclusion

HERA had a successful start up of luminosity operation. No unpleasant surprises have been encountered in electron proton collision and beam-beam interaction. E-p collisions are delicate but well under control. All effects observed so far can be understood, at least qualitatively, by single particle models of the motion of the proton beams. In the just starting 1993 operation, 84 bunch pairs are being collided. We expect a considerable increase of luminosity in the near future.

REFERENCES

[1] W. Bialowons, in Proceedings of the HERA Seminar 1993, Bad Lauterberg

[2] B. Wiik, this conference

[3] S. Levonian, DESY HERA 92-07 (1992) ZEUS Luminosity Monitor Group, DESY 92-066 (1992)

[4] J. Rossbach, DESY 89-023 (1989)

[5] S. Herb and F. Zimmermann, Proc. of the XV Int. Conf. on High Energy Acc Hamburg (1992), p227

[6] B.A. Baklakov et al, INP Novosibirsk preprint 91-15 (1991)

[7] R. Brinkmann, DESY-HERA 89-24 (1989)

[8] L. Evans and J. Gareyte, Cern82-8)(DI-MST)(1982)

[9] F. Zimmermann, thesis, University of Hamburg (1993) unpublished