Contribution to the ICFA
Newsletter May 2003

Experiences with the HERA beams

Georg Hoffstaetter, Mathias Vogt, and Ferdinand Willeke

for the HERA Luminosity upgrade group

After the design luminosity of the electron-proton collider HERA had been exceeded [1,2], the interaction regions were rebuilt to obtain smaller β^* at the two interaction points (IPs) [3,4,5]. Spin rotators on both sides of the IPs were installed to achieve collisions with longitudinal electron or positron polarization. Since the new interaction regions incorporate combined function magnets within the experimental solenoids' fringe fields, it is not trivial to achieve the longitudinal spin alignment with the precision required to avoid depolarization of the beam. Data is here presented, illustrating that this precision has been achieved. The desired increase in specific luminosity was quickly obtained after the upgrade of the interaction regions (IRs), but operating the detectors with full beam currents has not been possible due to too large background signals in H1 and in ZEUS. Currently a number of improvements are being implemented to reduce this background. The tests that are presented here show how the planed increase of the beam currents should translate into an increased absolute luminosity. In this context, experiences with the beam-beam force in HERA are important and will be described.

HERA

With a length of 6335m, HERA is the largest accelerator at DESY in Hamburg. It provides collisions between a 920GeV proton beam and a 27.5GeV polarized electron or positron beam and supplies four high energy physics experiments. Since all data that will be shown has been obtained with positrons, we only refer to positrons in the following, even though HERA can also accelerated electrons. H1 and ZEUS are the world's only high-energy e/p collider experiments; HERMES and HERA-B have a fixed target. HERA-B scrapes the proton halo with wires, and HERMES has a polarized gas storage cell target in the polarized electron or positron beam to analyze the polarized quark-gluon-structure of the nucleons. Before the IR-upgrade, HERMES was the only experiment which could take advantage of the typically 60% polarization of the electron or positron beam, since only around this experiment spin rotators brought the spins in a longitudinal direction. Now, 6 spin rotators align the positron polarization longitudinally in H1 and ZEUS as well.

HERA Upgrade

For equal proton emittances $\epsilon_{px}=\epsilon_{py}$ and assuming that the proton beam sizes at the interaction point can always be matched by the positron beam ($\sigma_{ex/y}=\sigma_{px/y}$), the following equation

$$L=\frac{N^{p}_{ppb}}{\epsilon_{px}}\frac{I_e}{4\pi e}\frac{1}{\sqrt{\beta^*_{px}\beta^*_{py}}}$$

shows that the luminosity can be increased by boosting the brightness $N^{p}_{ppb}/\epsilon_{px}$ of the p beam, by increasing the e current I_e, or by a decrease of the proton beta functions β^{*}_{px} and β^{*}_{py} at the collision points. These three measures have been found to be about equally expensive, but modifying the interaction region for obtaining smaller betas was the method of choice. In order to focus the proton beam stronger in the experimental region, the positron beam has to be separated from the proton beam as early as possible [3,4,5,6]. Whereas the first proton quadrupole had been 26m after the IP, this distance is now 11m. Additionally the upgrade project included 60m long spin rotators at both sides of the H1 and ZEUS detectors. The complete upgrade involved 448m of new vacuum pipes, 4 superconducting magnets for early separation of the e and p beams inside the detectors with a distance of only 2m from the IP, and 54 normal conducting magnets. The superconducting magnets have been built by BNL, and the Efremov Institute in St. Petersburg has built the normal conducting magnets.

Important parameters of previous HERA operation and the design parameters of the upgraded HERA are shown in the following table:

Parameters	HERA I		Design goal HERA II		Achieved	
	e-ring	p-ring	e-ring	p-ring	e-ring	p-ring
E(GeV)	27.5	920	27.5	920	27.5	920
I(mA)	50	106	58	140	10-40	20-100
$N_{ppb}(10^{10})$	3.5	7.3	4.0	10.3	1-3.5	4-7.5
n_{tot}	189	180	189	180	10-189	10-180
n_{col}	174	174	174	174	10-174	10-174
β_x*(m)	0.90	7.0	0.63	2.45	0.63	2.45
β_y*(m)	0.60	0.5	0.26	0.18	0.26	0.18
ϵ_x(nm)	41	$5000/\beta\gamma$	20	$5000/\beta\gamma$	20	$4000/\beta\gamma$
ϵ_y/ϵ_x	10%	1	17%	1	15%	1
σ_x/σ_y(μm)	192/50	189/50	112/30	112/30	113/25	
σ_z(mm)	11.2	191	10.3	191	-	150-200
$2\Delta\nu_x$	0.024	0.0026	0.068	0.0031	-	-
$2\Delta\nu_y$	0.060	0.0007	0.103	0.0009	-	-
Polarization	60%	0%	45%	0%	50%	0%
$\mathscr{L}$s	$6.70\cdot10^{29}$		$17.9\cdot10^{29}$		$24.\cdot10^{29}$	
$\mathscr{L}$	$0.172\cdot10^{32}$		$0.744\cdot10^{32}$		$0.27\cdot10^{32}$	

The achieved polarization and the achieved luminosities are discussed below. Since the specific and the absolute luminosities $\mathscr{L}$s and $\mathscr{L}$ were not obtained with the same set of parameters, the last two columns are only partially filled.

Polarization

Before the IRs were rebuilt, 60% positron polarization were routinely obtained. Due to the radiative Sokolov-Ternov buildup of polarization, the radiation is vertical in HERA's arcs. While a pair of dipole spin rotators rotated the polarization to the longitudinal direction in HERMES already since 1994 [7], the polarization in H1 and ZEUS used to be transverse. The experimental solenoids rotated this polarization around the longitudinal direction, but a counter solenoid subsequently compensated this perturbing effect so that the vertical polarization coming from one arc arrived vertical at the following arc after passing through the IR. For lack of space, the new IRs do not have counter solenoids and a vertical spin coming from one arc would not arrive vertically at the next arc if it were not rotated first, to be longitudinal in each IP's solenoid. With the new IRs, an accurate setting of the newly installed spin rotators right and left of H1 and ZEUS is therefore essential to obtain a polarized beam in HERA [8]. Obtaining such an accurate setting is not trivial since the spins move in the superimposed fields of combined function magnets and the fringe fields of the solenoids, which are not very accurately know. Nevertheless, 54% polarization was quickly achieved after all 3 pairs of spin rotators of HERA were switched on. Figure 1 shows the successful optimization of polarization.

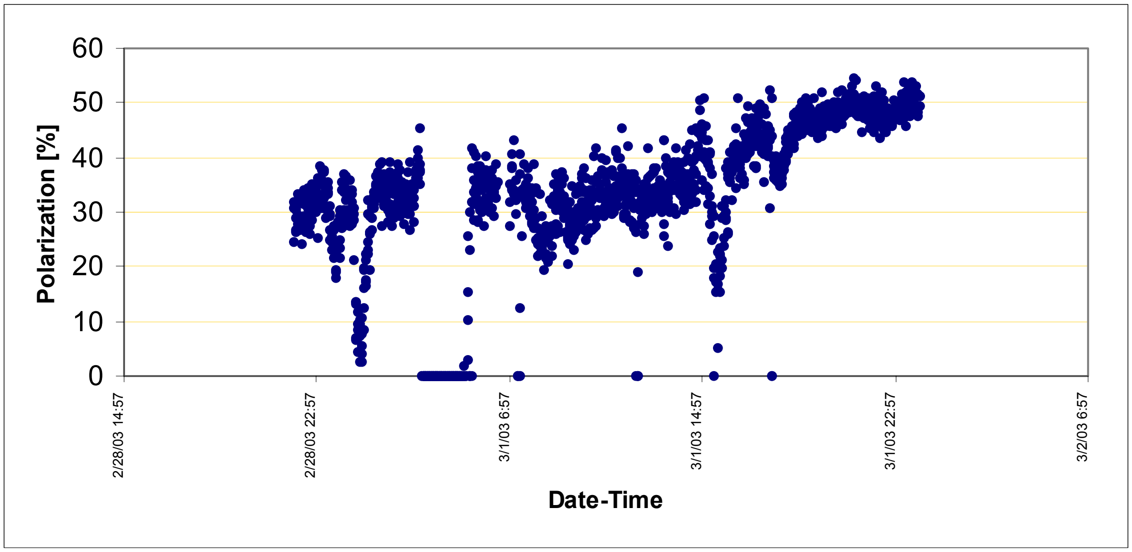

Figure 1: Polarization optimizations with 3 pairs of spin rotators in HERA-e on the 1st of March 2003. A polarization of 54% was ultimately obtained.

Luminosity

The required specific luminosity was reached relatively early on [9,10], when the polarization was not optimized and when the beam currents were low, so that the background in the detectors was not a limiting factor. Figure 2 shows that specific luminosities were reached that are higher than the design goal. For typical proton beam intensities as reached during the year 2000 running, the specific luminosity is close to the design value.

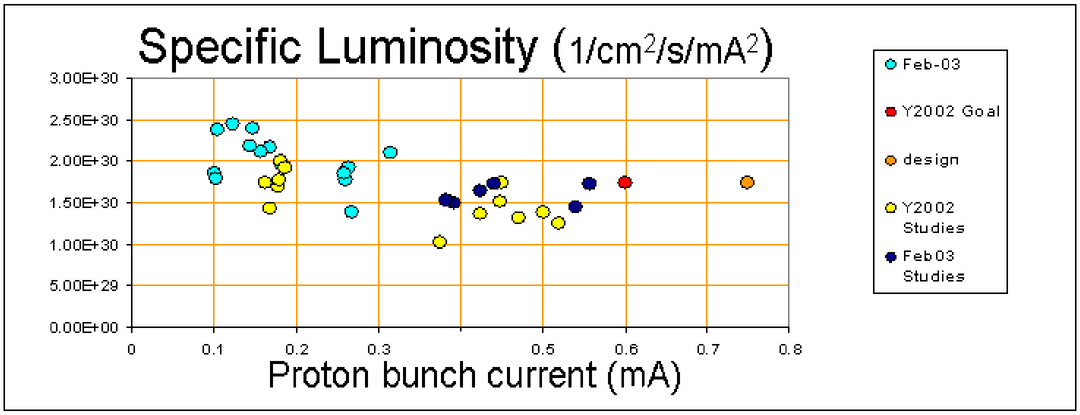

Figure 2: Specific luminosity versus proton bunch current.

The highest absolute luminosity of $2.7\cdot10^{31}$/cm^2/s that has been reached is illustrated in Fig. 3 (left). It is shown that the achieved luminosity varies linearly with the product of the proton bunch current and the total positron current. The right hand side of Fig. 3 shows the luminosity that would be expected if one scales to 174 colliding bunches, as a function of the product of the bunch currents. Up to values corresponding to the year 2000 bunch intensities, there is also a linear dependence. This indicates that the beam-beam force does not pose a limit up to this level of intensity. Up to now, the product of the proton and the positron beam current has been limited by the detector backgrounds, but after the installation of improved shielding by the end of June 2003 [11,12], nominal beam currents should be achievable. Figure 3 suggests that without this limitation on the total beam currents, a luminosity of about $5\cdot10^{31}$/cm^2/s should therefore be achievable. No luminosity data are available yet for proton bunch intensities that exceed the year 2000 values.

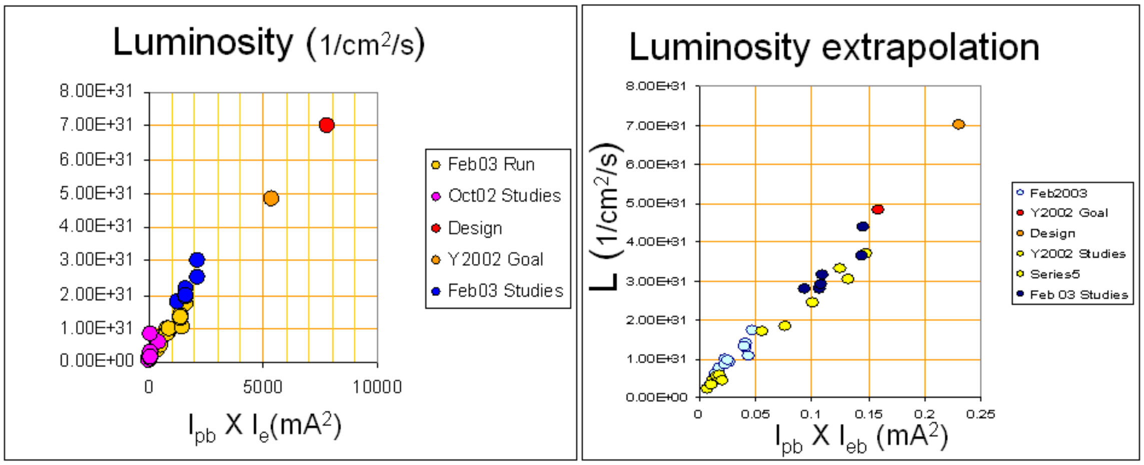

Figure 3: Achieved absolute luminosity as a function of the product of the proton bunch current and the total positron current (left). Expected luminosity when the positron current is scaled to its design value. Note that this does not change the beam-beam force for the positrons.

Observations about the Beam-Beam Interaction

While it has been observed that the proton lifetime decreases and the halo production, as measured by the wire of the HERA-B target, increases with increasing positron bunch current [13,14], the luminosity has not been shown to be deteriorated strongly by the beam-beam force acting on the protons. This indicates that the nonlinear beam-beam force affects protons with large transverse amplitudes, whereas it does not yet deteriorate the core of the proton bunches. Furthermore the resonance strength of proton dynamics including the influence of the hourglass effect on the proton's beam-beam force has been studied for the parameters of the new IRs [15,16].

Before HERA's IRs were changed, it was investigated whether the beam-beam force deteriorates the positron beam so that the specific luminosity would diminish with increasing positron bunch current. As shown in Fig. 4, such a correlation was not observed when plotting the specific luminosities as a function of proton bunch current for all runs of the first four months of the year 2000.

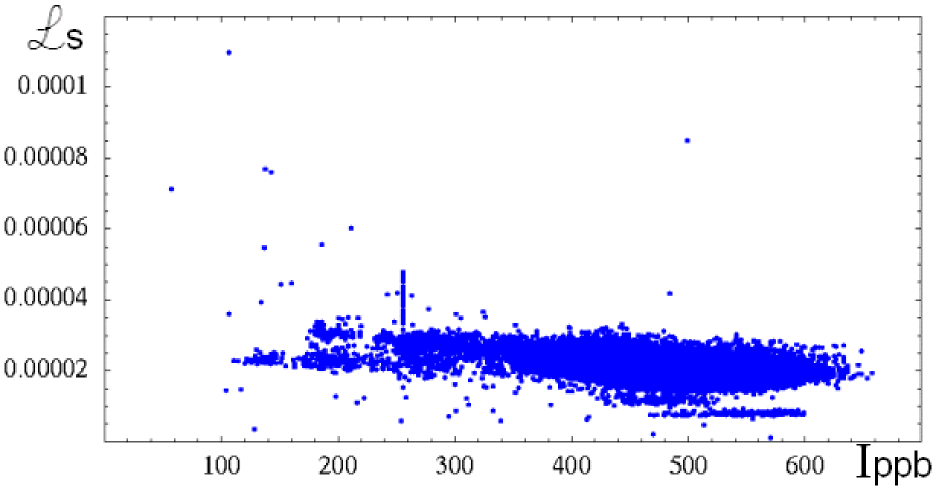

Figure 4: The specific luminosity $\mathscr{L}$s (arbitrary units) for each colliding bunch against the proton bunch current I_p(μA) as obtained by H1.

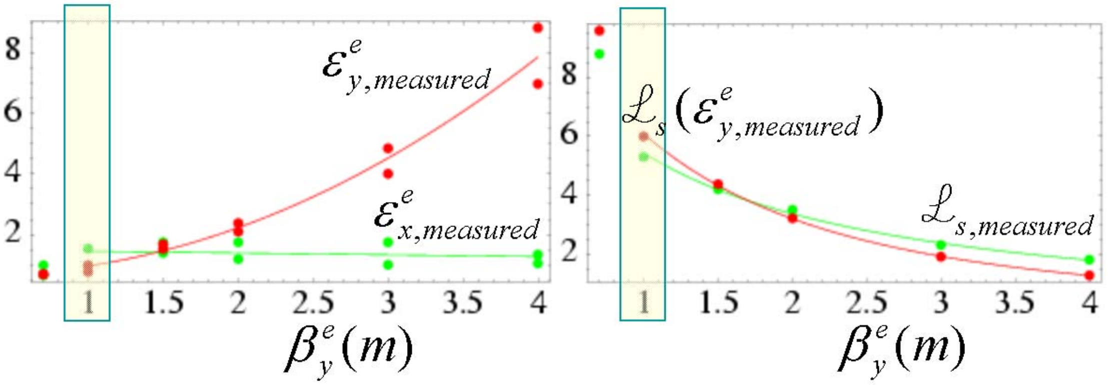

Figure 5: Measured emittances of the positron beam as a function of vertical beta function (left). Beasured and computed specific luminosity (right).

Since the vertical beam-beam tune shift of the lepton beam will increase by 50% compared to the year 2000 operation, when nominal proton currents are filled, the tune shift limit has been explored with the old IRs by increasing the positrons' β^*_{ey} [17]. Values of β^*_{ex}=2.5m (corresponding to the expected horizontal tune shift with 140mA of protons) and β^*_{ey}= 1m,1.5m,3m, and 4m have been implemented and collided with a 90mA proton beam. The e and p beam sizes were not matched. We observed a monotonically increasing blow-up of the vertical lepton emittance with increasing β^*_{ey} by factors up to 8 as shown in Fig 5 (left). At the value of β^*_{ey}=1.5m which corresponds to a vertical beam-beam tune shift of 0.069, the blow-up factor was 1.5. Figure 5 (right) shows the measured specific luminosity and the luminosity computed from the measured beam emittances. The lifetime and operation conditions were good even with the tune shift of 0.5. This is probably due to a depopulation of the bunch center. This is also indicated by the fact that the shift in the coherent oscillation frequency for β^*_{ex}=2.5m and β^*_{ey}=4m was measured to be only $\Delta\nu_x$=0.009 and $\Delta\nu_y$=0.013 while it would be $\Delta\nu_x$=0.027 and $\Delta\nu_y$=0.082 if both beams were Gaussian. The latter values were computed with a simple formula for the coherent beam-beam tune shift for Gaussian beams of unequal sizes [13] in the weak-strong limit, i.e. under the assumption that the proton beam acts as a fixed nonlinear lens:

$$\Delta\nu_{ex} = \xi_{ex}\frac{\sigma_{px}(\sigma_{px}+\sigma_{py})}{\Sigma_x(\Sigma_x+\Sigma_y)}, \quad \Delta\nu_{ey} = \xi_{ey}\frac{\sigma_{py}(\sigma_{px}+\sigma_{py})}{\Sigma_y(\Sigma_x+\Sigma_y)},$$

$$\Sigma_x = \sqrt{\sigma_{ex}^2+\sigma_{px}^2}, \quad \Sigma_y = \sqrt{\sigma_{ey}^2+\sigma_{py}^2}.$$

Recent simulations with the specified beam parameters have yielded a coherent tune shift of $\Delta\nu_x$=0.003 and $\Delta\nu_y$=0.013. While the horizontal tune shift is close to the resolution of the calculation and therefore not very trustworthy, the agreement of the vertical tune shift with the measurement is quite remarkable [18].

In recent measurements with the new IRs, the beam-beam force on the e beam has influenced the luminosity adversely. Fig. 6 shows the specific luminosity and the proton bunch current for each e/p bunch pair for an irregularly filled HERA-p. It is very apparent that the pairs with higher proton current have lower specific luminosity. Furthermore Fig. 7 shows that the simple formula, given above, describes the coherent tune shift rather well for low proton bunch currents, indicating that the e beam has a Gaussian distribution. For larger proton bunch currents the tune shift deviates from the simple formula, indicating that the beam-beam force has altered the particle distribution of the e beam. This effect is being studied in more detail.

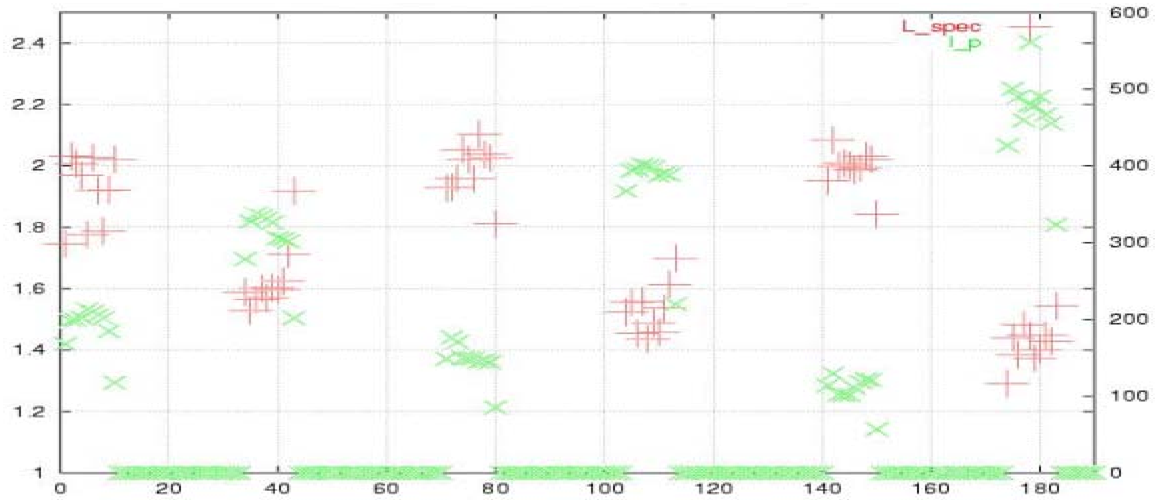

Figure 6: Specific luminosity (red, +) for different proton bunch currents (green, X).

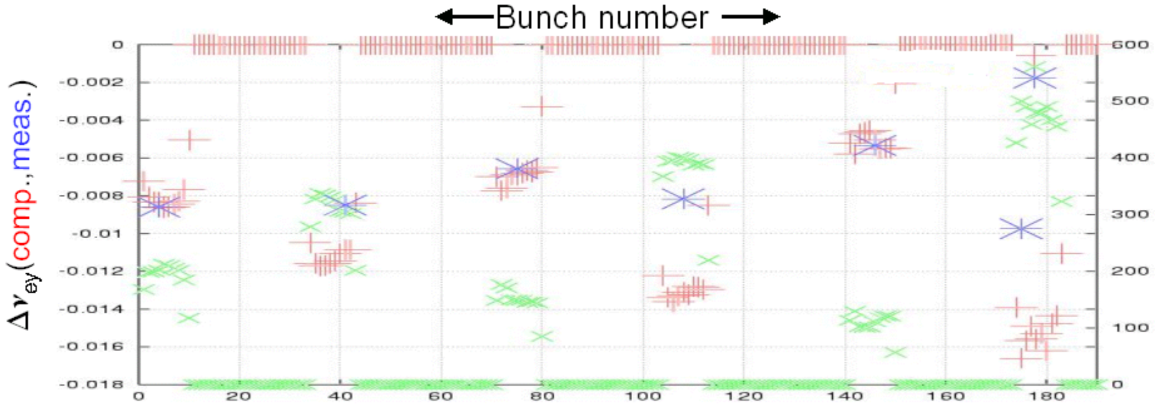

Figure 7: The vertical coherent tune shift $\Delta\nu_{ey}$ per bunch for different proton bunch currents (green, X): computed tune shift for all 60 bunches (red, +) and measured tune shifts for one bunch per train of 10 similar proton bunches (blue, +x).

Since the beam-beam forces on the e beam become relevant, simulation studies of this effect are being continued and optical measures are being analyzed that should minimize the influence of the beam-beam forces in the two IPs.

References

[1] G.H.Hoffstaetter, “Future Possibilities for HERA”, Proceedings EPAC, Vienna (2000)
[2] G.H.Hoffstaetter and F.Willeke, “Future HERA High Luminosity Performance”, Proceedings HEACC01, Tsukuba (2001)
[3] U.Schneekloth (ed.), “The HERA Luminosity Upgrade”, Report DESY-HERA-98-05 (1998)
[4] M.Seidel, “The Upgraded Interaction Regions of HERA”, Report DESY-HERA-00-01 (2000)

[5] M.Seidel, “Layout of the Upgraded HERA Interaction Regions”, Proceedings of EPAC00, Vienna (2000)
[6] G.H.Hoffstaetter, “Electron Dynamics after the HERA Luminosity Upgrade”, Proceedings EPAC 2000, Vienna (2000)
[7] D.P.Barber et al., “The first achievement of longitudinal spin polarization in a high energy electron storage ring”, Phys.Letts., B343, p.436 (1995)
[8] M.Berglund, “Spin-orbit maps and electron spin dynamics for the luminosity upgrade project at HERA”, Doctoral Thesis, Royal Institute of Technology, Stockholm, June 2001 and Report DESY-Thesis-2001-044 (2001)
[9] G.H.Hoffstaetter, “Luminosity Scans at HERA”, Proceedings EPAC 2002, Paris (2002)
[10] M.Dohlus, G.H.Hoffstaetter, M.Lomperski, R.Wanzenberg, “Report from the HERA Taskforce on Luminosity Optimization. Theory and First Luminosity Scans”, Report DESY-HERA-2003-01 (January 2003)
[11] “Further Report on Beam-Induced Backgrounds in the H1-Detector”, Notes H1-10/02-606, H1-01/03-607 (2003)
[12] “Study of beam-induced backgrounds in the ZEUS detector from 2002 HERA running”, Notes ZEUS-02-018, ZEUS-02-020, ZEUS-02-027 (2002)
[13] M.Bieler, E.Gianfelice, G.H.Hoffstaetter, T.Limberg, M.Minty, and F.Willeke, “Experiments about the Beam-Beam Effect at HERA”, in [14] (2000)
[14] G.H.Hoffstaetter (ed.), “HERA Accelerator Studies 1999”, Report DESY-HERA-00-02 (May 2000)
[15] G.H.Hoffstaetter and F.Willeke, “Beam-Beam Limit with Hourglass Effect in HERA”, Proceedings EPAC 2002, Paris (2002)
[16] G.H.Hoffstaetter and F.Willeke, “Future HERA High Luminosity Performance”, Proceedings of HEACC 2001, Tsukuba (2001)
[17] G.H.Hoffstaetter (ed.), “HERA Accelerator Studies 2000”, Report DESY-HERA-00-07 (2000)
[18] Jack Shi, University of Kansas, Private communication (2002)