HERA PERFORMANCE UPGRADE: ACHIEVEMENTS AND PLANS FOR THE FUTURE

M. Minty, DESY, Hamburg, Germany

Abstract

With the design luminosity already surpassed in 1997, an ambitious upgrade of the HERA proton-lepton collider was installed in 2000/2001 to provide higher luminosity and longitudinally polarized lepton beams in the colliding beam experiments, H1 and ZEUS. Initially, experimental backgrounds limited the total beam currents. After completion of the HERA-B experiment in 2003, the number of colliding bunches was reduced while maintaining the same total beam currents to increase the single-bunch beam currents. With pre-upgrade bunch currents the specific luminosity was measured to be 3 times higher with the upgrade. Following modifications which helped to alleviate the detector backgrounds in 2003 and an extended period of steady operation, HERA is now operating with the design number of bunches while the total beam currents $I_p \times I_e$ are being steadily increased. With less than 60% of the total design current, peak luminosities of 3.5×10^{31} cm^{-2}s^{-1} have been demonstrated with a longitudinal polarization at the interaction points exceeding 50%. In this presentation experience with the luminosity upgrade and future plans will be described.

INTRODUCTION

The 6.3 km double-ring collider km HERA [1] accelerates about 100 mA of protons to an energy of 920 GeV for interactions with 27.5 GeV leptons with currents of about 50 mA (e+) or 40 mA (e-) using 174 colliding bunches. Commissioning of the accelerators took place in 1991/92 with first collisions in 1991. Over the next few years the luminosity produced by HERA increased steadily [2] as experience was gained, for example, in combating the effects of eddy currents in the super-conducting magnets [3-5] and in optimizing the parameters relevant for controlling the proton beam lifetime with beams in collision [6]. The design luminosity of 1.4×10^{31} cm^{-2}s^{-1} was surpassed in 1997 [7].

The integrated luminosity was further increased following an extensive program for improving accelerator availability [7,8] in 1997/98. This effort included a) replacement of the vacuum pumps (to minimize the detrimental effects of "dust") in the lepton ring, which is relevant for operation with electrons [9,10]; b) the addition of more rf systems in the lepton accelerator to allow for higher beam currents; c) improvements (i.e. addition of a bias voltage for the couplers of the superconducting cavities) and replacement of various elements (i.e. power supplies and low beta-quad coils) to enhance reliability, d) aperture increases in the injection beamlines, and e) an upgrade of the controls system.

Having surpassed the design goal for peak luminosity with an integrated luminosity consistent with expectation, an upgrade was deemed necessary to significantly increase the luminosity. The constraints on colliding beam performance prior to the upgrade may be seen using the following expression for the total luminosity assuming matched beam sizes, no variations in bunch parameters across the bunch trains, and head-on collision:

$$\mathrm{L} = \frac{\gamma_p}{2\pi e}\frac{(\frac{\mathrm{N}}{\epsilon})_p \cdot \mathrm{I_e}}{\sqrt{\beta^*{}_{xp}\beta^*{}_{yp}}} \qquad [1]$$

where γ_p=E_p/m and the variable parameters are the proton beam brightness $(N/\varepsilon)_p$ with N the number of protons per bunch and ε the normalized proton beam emittance, I_e the total lepton current, and β^*_{xp} / β^*_{yp} respectively the horizontal and vertical proton beam beta-functions at the interaction point (IP).

The *proton beam brightness* $(N/\varepsilon)_p=10^{11}/4\mu$m was limited by space charge effects in the preaccelerators and in HERA potentially by the increase in lepton beam tune spreads or emittances as a function of single-bunch proton beam current. The *total lepton beam current* I_e (~60 mA, design) was and still is limited by total available rf power and potentially (particularly of initial concern for the luminosity upgrade with smaller lepton beam sizes) by the tune spread imparted to the protons from the beam-beam interaction. The *proton beta functions* at the IP, β^*_{xp}=7m and β^*_{yp}=50 cm were limited by the geometry of the interaction region.

THE LUMINOSITY UPGRADE [11]

Given the limitations just described, the most cost-effective and conservative option for a substantial luminosity increase was considered to be modifications to the HERA interaction regions (IRs) to allow for smaller β-functions at the collision points (as opposed to extensive rf system upgrades and aperture modifications in the preaccelerators and HERA). The layout of the interaction region [12] which facilitates stronger focussing of the proton beam (β^*_{xp} =2.45m and β^*_{yp}=18 cm) is shown in Fig. 1. The essential feature of the modifications include the superconducting combined-function quadrupoles with separator fields placed inside the detectors. Special collimation and masking inside the detectors are included to shield from up to 28 kW of synchrotron radiation power produced by the separation magnets [12].

With this geometry the proton beam sizes (in μm) at the interaction point were reduced from 190/50 (horizontally/vertically) to 112/30. To match the lepton beam sizes to those of the protons, in addition to the stronger focussing of the lepton beams in the IRs, the emittance was reduced by a combination of an increased betatron phase advance (from 60 to 72 degrees per FODO cell) and an rf frequency shift [13].

Installation of the new interaction regions took place in 2000/2001. In total, over 250 m of new vacuum chambers (proton, lepton, and synchrotron light) were installed at each interaction region, which includes new 60m long spin rotators on both sides of the H1 and ZEUS colliding-beam experiments to provide for longitudinally polarized leptons.

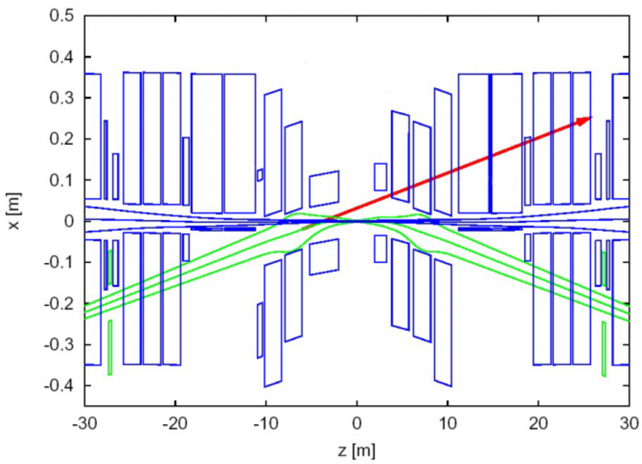

Figure 1: Layout of the new interaction regions [12].

EXPERIENCES SINCE THE UPGRADE

Accelerator commissioning with the upgraded interaction regions began in late 2001 and continued through the fall of 2002. During this time the total beam currents were limited by unexpectedly high background rates in the detectors. Until the maintenance period in the spring of 2003, the nominal current distributions (e.g. number of bunches) were used in support of the HERA-B experiment, which preferred lower single-bunch intensities and high total beam currents. During commissioning many operational improvements were implemented to further improve accelerator performance. In early 2003 the essential design features of the luminosity upgrade were validated using reduced number of bunches and nominal (i.e. pre-upgrade) single-bunch beam currents. During these dedicated studies, the design beam parameters and a 3-fold increase in specific luminosity were demonstrated. During the 2003 shutdown, which marked the end of the HERA-B experiment, modifications were made to help mitigate certain background issues. Since then the total beam currents in HERA continue to be increased and both the integrated and peak luminosities delivered to the experiments are rising steadily. In the following we summarize the most important activities from commissioning of the luminosity upgrade.

Detector Backgrounds

A relation for the leakage current in the central tracking chambers of the high energy physics detectors arising from backgrounds I_{bg} was developed with predictive power for extrapolation to higher beam currents [14,15]:

$$I_{bg}=c_0+c_1I_e+c_2I_e^2+c_3I_p+c_4I_eI_p \qquad [2]$$

where I_e and I_p are respectively the total lepton and proton beam currents and the c_i are constants determined in dedicated studies. The various terms have physical interpretations: c_0 [μA] –detector pedestal, c_1 [μA/mA] – direct synchrotron radiation, including back-scattered radiation produced by the high-energy leptons, c_2 [μA/mA^2]– vacuum related lepton beam-gas scattering arising in part from higher-order-mode heating, c_3 [μA/mA] – beam-gas scattering of protons, and surprisingly the c_4 term [μA/mA^2]– proportional to the product of the total beam currents $I_p \times I_e$. Until the 2003 shutdown, the last term was seen to dominate.

The source of this term is now interpreted to be unique for high-energy leptons colliding with proton beams: the synchrotron radiation generated by the leptons causes enhanced desorption of gas from the vacuum chamber walls (some of which are cooled to 40K).

With the exception of the pedestal, the amplitude of all the coefficients c_i has been observed to decrease as a function of time as shown in Fig. 2 from the H1 experiment. In particular, the dominating term proportional to the product I_eI_p has reduced considerably. The detector currents at the ZEUS experiment, as shown in Fig. 3, have also improved significantly. Based on the measured background rates, a warm-up procedure, taking place during planned maintenance periods, is implemented to maintain good vacuum and background conditions.

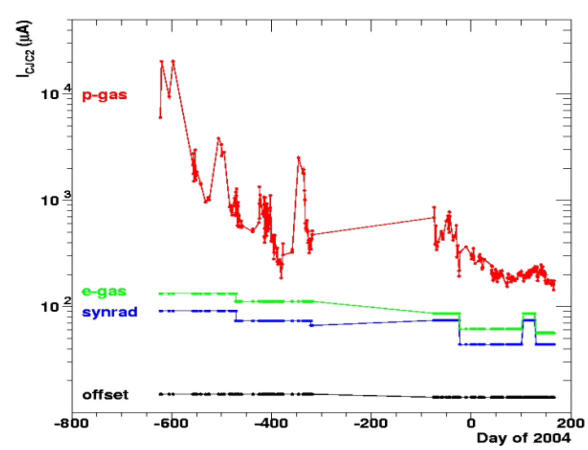

Figure 2: Contributions to the detector leakage currents (e.g. the terms in Eq. 1) versus time with I_e=50 mA and I_p=100 mA based on measured background coefficients at the H1 experiment (courtesy C. Niebuhr).

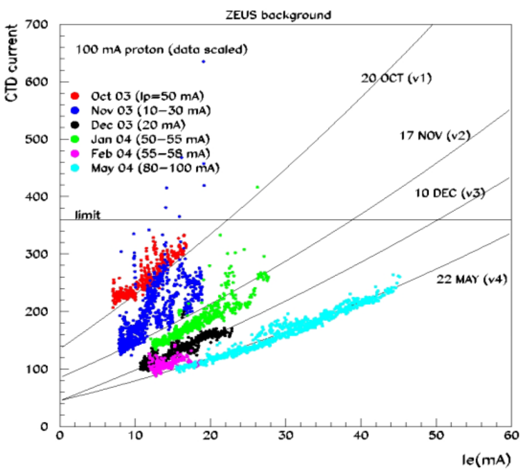

Figure 3: Background rates versus lepton beam current scaled to I_p=100 mA at ZEUS (courtesy U. Schneekloth).

During the 2003 shutdown modifications were made in the masking (change in shielding against twice back-scattered synchrotron radiation) at one of the experiments, an additional vacuum pump was added in the other, and the conductance of pumping ports was increased by a factor of 2 in certain critical areas. Earlier, additional collimators (outside of the region of the HERA upgrade) were also added to provide shielding from far upstream scattering sources. While the masking at the one experiment was critical, vacuum conditioning with beam and routine warm-ups appear to be most effective in reducing the backgrounds. Since the shutdown, the background rates at the experiments are acceptable and there are no limitations on the total beam currents.

Operational improvements

Of the many improvements implemented, beam-based alignment (BBA) in the new compact IRs and feedback loops for orbit stabilization have proven particularly effective. The BBA of the combined function magnets was developed [16,17] to better control the magnetic optics and to minimize spurious synchrotron radiation generated by off-axis beams. Time-dependent orbit fluctuations, arising in part from magnet displacements due to magnetic forces, are now controlled using automated orbit steering [18] to reference orbits allowing superimposed closed-orbit bumps thus further reducing the possibility of localized heating.

Verification of the upgrade parameters

While still limited in total beam currents, accelerator studies were undertaken using about 2/3 of the nominal number of colliding bunches and single-bunch beam currents equal to those of prior to the upgrade. The experiments [19] validated the design beam parameters and a 3-fold increase in specific luminosity. Shown in Fig. 4 are the beam currents (top) and total luminosity (bottom) measured with collisions in one interaction region. Despite the reduced total beam currents, a total luminosity of 2.7×10^{31} cm^{-2}s^{-1} was demonstrated in these dedicated experiments.

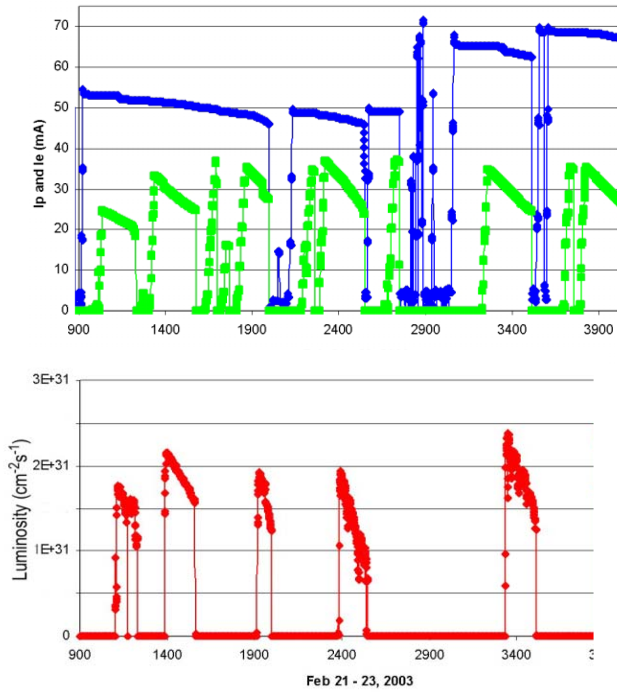

Figure 4: Proton and lepton beam currents (top) and total luminosity measured with reduced number of colliding bunches in experiments which validated the parameters of the luminosity upgrade [19].

Beam Dynamics: synchro-betatron resonances

The nominal operating point in the HERA lepton tune diagram is selected to allow for build-up of high lepton beam polarization. With this constraint, the choice of horizontal lepton beam tune is between the 2nd and 3rd order synchrotron sideband resonances. Following the upgrade, with smaller synchrotron tune resulting from the smaller momentum compaction factor, synchro-betatron resonances [20] posed initially considerable operational difficulties (e.g. beam loss). This difficulty was solved [20] using a new lattice with a betatron phase advance between experiments of precisely $\pi/2$.

Beam Dynamics: the beam-beam interaction

The small proton beam sizes at the collision points in the upgraded lattice give rise to significant beam-beam effects on the lepton beam: 1) the linear beam-beam tune shift parameters of the leptons at each of the two interaction points are $\Delta\nu_x$=0.020 horizontally and $\Delta\nu_y$=0.045 vertically; 2) with a horizontal tune of Q_x=54.12 close to integer, the additional focusing of the leptons by the protons (the so-called dynamic beta effect) can be considerable and the resulting beam-beam induced beta beat is suppressed using a special optic and phase trombones to produce a phase advance of exactly $\pi/2$ between the two interaction points; 3) the lepton beam tune spreads at nominal proton single-bunch currents are close to 0.1 in the vertical plane and close to 0.05 in the horizontal plane, which restricts the choice of possible betatron tunes whereby the influence of beam-beam and lattice nonlinearities is critical.

While many experiments were performed prior to the luminosity upgrade under special conditions created to simulate the expected conditions [21,22], confirmation of certain aspects of the beam-beam interaction could take place only following the upgrade of both the interaction regions and accelerator optics. In dedicated studies [23] many effects were identified which resulted in decreased specific luminosity: lepton and proton beam emittance growth arising from beam-beam resonances, the dependence of proton beam emittance on proton beam current, lepton beam emitttance growth from normal (and later, from synchro-betatron) resonances, and the effects arising from the presence of two interaction points.

A striking example is shown in Fig. 5, which shows the vertical emittance of the lepton beam as a function of the single-bunch proton current. Using single-bunch measurements of the betatron tunes, the bunches colliding with high intensity proton bunches were observed to "lock" onto a skew resonance at Q_y=-3Q_x, which is not naturally driven by the bare lattice. Given the symmetry of the beam-beam potential, the even order resonance 2Q_y=-6Q_x can be driven by the beam-beam interaction.

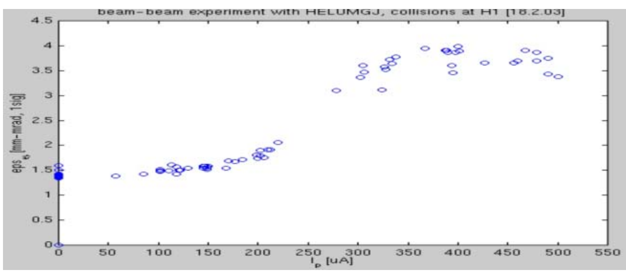

Figure 5: Lepton beam emittance versus single-bunch proton current evidencing growth due to a beam-beam resonance at 2Q_y=-6Q_x.

As predicted by simulations of the beam-beam interaction in the strong-strong model [24], the lepton bunches have occasionally been observed to perform coherent dipole oscillations. The proton bunches are then continuously excited by the leptons which leads to an ~10% increase of the proton transverse emittances. The effect is observed to depend strongly however on both lepton and proton betatron tunes. Under worst conditions with the lepton tunes too close to a resonance (in this case Q_x+3Q_s=0), the proton beam emittances have been observed to increase by factors of 2-4. Such emittance growth is now avoided by precisely controlling the betatron tunes of both beams and by bringing the beams into collision sequentially at the two interaction points.

Lepton beam polarization

The performance upgrade includes longitudinally polarized lepton beams in the colliding beam experiments. To achieve this additional pairs of spin rotators were added on both sides of the IPs. A spin-matched optics was developed [25] taking into account the non-local compensation of the detector solenoidal fields and the increased betatron coupling required to match the vertical beam sizes at the IPs. Shown in Fig. 6 is the measured polarization during commissioning of the new spin with the rotators turned on but without the detector solenoids (left), with the rotators and solenoids turned on (middle), and with beams in collision (right) evidencing a polarization exceeding 50%.

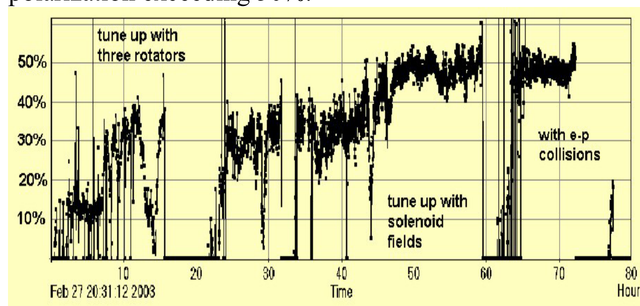

Figure 6: Polarization at HERA obtained during commissioning of new spin rotators for producing longitudinally polarized leptons for collisions with protons [25].

PRESENT PERFORMANCE AND FUTURE PLANS

With the detector leakage currents substantially reduced by improved masking at one of the two experiments and by rigorously enforcing routine operations, which evidenced the strong influence of vacuum conditioning, HERA is now no longer limited in total beam currents and is operating with currents comparable (or exceeding) those used prior to the luminosity upgrade. The peak luminosities as measured in the two colliding beam experiments are shown together with expectation in Fig. 7, which demonstrates both high and steadily increasing luminosity as well as relatively good agreement between measurement and expectation. The integrated luminosities are given in Fig. 8.

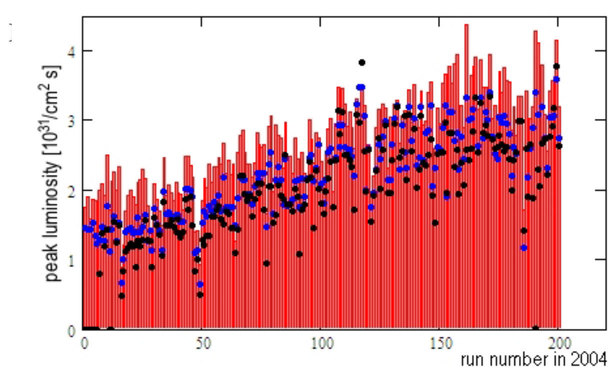

Figure 7: Peak luminosity for each run so far this year: estimates, based on measured beam parameters (red bars) and measurements at H1 (blue dots) and ZEUS (red dots).

Two effects substantially limited the integrated luminosity over the last ½ year. First, beam losses occasionally occurred, whereby the detected radiation level outside the tunnel proper reached the substantially reduced levels allowed for by new radiation safety rules. For about 2 months, the total proton beam current was administratively limited to 20 mA while countermeasures were developed (fast dumps based on measured power supply currents and beam orbits). The second effect relates to the production of dc proton beams, which caused spikes in the proton backgrounds at one of the experiments. The source was found to be a faulty cable which has since been replaced.

Present efforts aimed towards maximizing the integrated luminosity now focus on improving the accelerator availability and operational efficiency. The improvement program includes upgrading the low-level controls of the proton RF systems, adding more vacuum pumps in the lepton RF systems, and upgrading the cryogenic system (compressors and controls). The efficiency will be increased by improved beam position and profile instrumentation, software modifications for the collimation systems, and the addition of longitudinal damping in the proton ring for suppression of multibunch instabilities [26]. Improved damping should allow for better bunch length control during the energy ramp and enable full exploitation of the luminosity upgrade by reducing the hour glass effect and enabling a further decrease of the beta-functions at the interaction points.

Following a required shutdown for radiation interlock tests beginning in mid August, it is planned to begin operation with electron beams. The present operations schedule calls for the end of the HERA physics program in year 2007. Longer term possibilities for HERA were presented in Ref. [8].

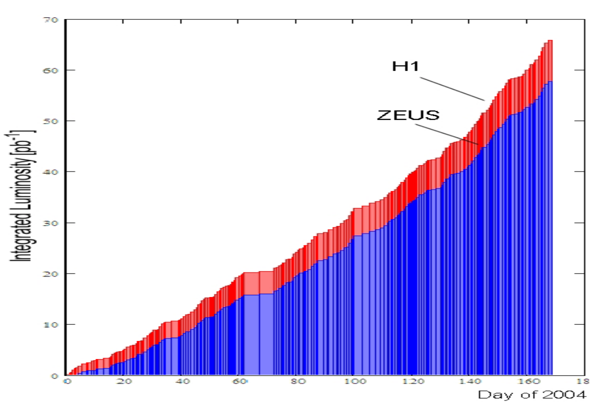

Figure 8: Integrated luminosity at the two HERA colliding beam experiments.

REFERENCES

[1] "HERA Proposal", DESY-HERA-81-10, 1981.
[2] W. Bialowons, "Status of HERA", EPAC96 (Sitges).
[3] R. Brinkmann, F. Willeke, "Persistent current field errors and dynamic aperture of the HERA proton ring", Proc. ICFA Beam Wksp. 1988:0203 (Lugano, Switzerland, 1988).
[4] F. Willeke, F. Zimmermann, "The impact of persistent current field errors on the stability of the proton beam in the HERA proton ring", PAC91 (San Fransisco, CA).
[5] S. Herb et al, "Experience with persistent current field errors in the HERA proton ring", Proc. HEACC92 (Hamburg), 398.
[6] R. Brinkmann, F. Willeke, "First experience with colliding electron proton beams in HERA", PAC93 (Washington, DC).
[7] F. Willeke, "HERA status and upgrade plans", PAC97 (Vancouver, BC).
[8] F. Willeke, "HERA status and perspectives of future lepton hadron colliders", EPAC02 (Paris).
[9] D.R.C.Kelly et al, "The electron beam lifetime problem in HERA', PAC95 (Dallas, TX).
[10] D.R.C. Kelly, W. Bialowons, K. Wittenburg,"HERA electron beam lifetime disruption machine studies and observations", EPAC96 (Sitges).
[11] U. Schneekloth (ed), "The HERA luminosity upgrade", DESY-HERA-98-05 (1998).
[12] M. Seidel and F. Willeke, "Layout of the upgraded HERA interaction regions", EPAC00 (Vienna).
[13] G.H. Hoffstaetter, "Electron dynamics after the luminosity upgrade", EPAC00 (Vienna).
[14] D. Bailey et al, "Study of beam-induced backgrounds in the ZEUS detector from 2002 HERA running", ZEUS-02-018.
[15] V. Andreev et al, "Technical report on the beam induced backrounds in the H1 detector", H1-10/02-606; V. Andreev et al, "Further report on beam-induced backgrounds in the H1 detector", H1-01/03-607.
[16] G.H. Hoffstaetter and F. Willeke, "Beam based alignment of interaction region magnets", Report DESY-02-069 (2002).
[17] F. Brinker et al, "Beam based alignment of combined function magnets in the upgraded HERA interaction regions", Proc. EPAC02 (Paris).
[18] S. Herb et al, "Automated orbit control for the HERA ep Collider", these preceedings.
[19] M. Minty, "Summary of recent high luminosity experiments after the HERA-II luminosity upgrade and future prospects", HERA-03-25.
[20] F. Willeke, "Synchro-betatron resonances in HERA-II", these proceedings.
[21] G.H. Hoffstaetter, "Observations about the HERA Luminosity", DESY HERA 00-07 (2000).
[22] G.H. Hoffstaetter and F. Willeke, "Electron dynamics in the HERA luminosity upgrade lattice of the year 2000", PAC99 (NewYork, NY).
[23] M. Minty, "Recent beam-beam experiments at HERA-II after the luminosity upgrade", HERA-03-21.
[24] J. Shi, L. Jin, G.H. Hoffstaetter, "Study of beam-beam effects in HERA with self-consistent beam-beam simulation", Proc. PAC03 (Portland, OR).
[25] E. Gianfelice and D. Barber, "Longitudinal Positron Polarization at HERA", these proceedings.
[26] E. Vogel, "Examination of the longitudinal stability of the HERA proton ring", EPAC02 (Paris).