HERA AND THE NEXT GENERATION OF LEPTON-ION COLLIDERS

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Abstract

A summary of the physics results of the lepton-hadron (ep) collider HERA, a review of lessons learned in view of the LHC, and possible future ep colliders, with emphasis on challenges and luminosity reach is presented.

INTRODUCTION

Collisions of high energy leptons with hadrons reveal the structure and dynamics and the nature of the forces between the constituents of hadrons. Electron scattering experiments on protons were performed already fifty years ago when R. Hofstadter and co-workers measured the nuclear form factor by analysis of (200-600) MeV electrons scattered on protons [1]. As leptons with energies of several GeV became available, a series of lepton nucleon scattering experiment revealed an inner structure of the proton with point-like constituents [2,3]. This discovery was followed by many experiments yielding a better understanding of the proton structure. The experiments E49-89 at SLAC [4] observed that the cross section for small x[†] remained constant in the range of $x \approx 1/3$-0.01. This result (among others) suggested that additional quarks-antiquark pairs are produced inside the proton by the strong force between the valence quarks and the gluons. A lepton-hadron collider with large centre of mass energy (E_{cm}) was expected to provide the ultimate experimental evidence for this model because it would provide access to small x with sufficient spatial resolution or high Q^2. At that time, the HERA ep collider with E_{cm} = 318 GeV was proposed [5]. HERA was expected to provide precision measurements of the proton dynamic structure function F_2, of electro-weak and strong interactions, and to provide experimental evidence of lepton quark resonances. HERA was approved in 1984 and the physics program was started in 1992.

HERA FEATURES, STATUS AND PLANS

HERA consists of two 6.4 km long storage rings, one with 5T superconducting magnets for the 920 GeV protons and another with normal conducting magnets for the 27.5GeV electrons or positrons. The beams collide at two collision points (IP) denoted by North and South, where the detectors H1 and ZEUS are located. The interaction regions (IR) were upgraded for a high luminosity of $L > 5\cdot10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 2001 [6]. The HERA lepton beam is spin polarized by the Sokolov-Ternov [7] effect. Spin rotators [8] around each experiment provide longitudinally polarized leptons for collisions with protons.

The low proton injection energy of 40 GeV into HERA and corresponding persistent current field errors [9] are the cause for a small dynamic aperture of only 3.8 RMS beam sizes $\sigma_{x,y}$ [10]. This serious issue is solved by strictly controlling the beam parameters. Emittance dilution at injection is avoided by correcting injection errors to < 1mm transversely and to $< 4\cdot10^{-4}$ in relative energy at each proton injection. The tunes during injection and the first part of acceleration must be kept to within a small window of $\Delta Q_{x,y} \leq 0.002$. They are controlled by a software-based feedback [11] with a non-destructive tune measurement [12]. Persistent and eddy current sextupole components of the guide fields must be suppressed dynamically to a level of 0.3% which is accomplished by a combination of continuous monitoring and correction via a reference magnet system, by look-up tables for correction of systematic errors and by fine tuning the chromaticity by hand based on analysis of the tune spectra. As a result, the chromaticities $\xi_{xy}=\Delta Q_{xy}\,({}^{\Delta p}/{}_{p})^{-1}$ are controlled to about one unit. The betatron-oscillations must be decoupled to levels of < 0.005 in the coupling strength. Failure to meet these requirements leads either to beam loss > 1% due to poor dynamic aperture, or multi-mode head tail instabilities. The head tail instability is driven by a conspiracy of coupling and small values of chromaticity [13]. Attempts to control the instabilities during acceleration by broadband dampers [14] have been abandoned because of significant emittance growth due to feedback noise and the then required PLL-type tune measurement, and, more importantly, due to the loss of information necessary to fine-tune the chromaticities based on analysis of the tune spectra for maintaining good lifetime. This part of HERA experience may be relevant for the LHC. High precision, non-destructive tune and chromaticity measurements in conjunction with low-noise damper systems are deemed necessary for the LHC.

HERA is unique in colliding very different particles. Stable operation requires matching the beam cross sections at the IP to ≤20% of the relative beam size. The bunch intensity of both beams is limited by the beam-beam effect suffered by the opposite beam. The vertical beam-beam tune shift parameters at two collision points reach levels of $\Delta\nu_{ye}$=0.05 for leptons and around $\Delta\nu_{yp}$=0.001 for protons. The proton beam-beam effect is a soft limit. Increasing beam-beam forces produce a gradual increase in experimental background by increased diffusion of protons into the beam halo. Orbit stability is therefore most critical. If the beam retracts from the collimators, diffusing particles fill the gap between beam edge and collimators and are lost on the next approach to the collimators [15]. The collimation system has a leakage of about 1% [16]. This causes a sudden increase in background which is not tolerable. Power supply ripple,

[†] The parameter x is the fractional momentum of the interacting proton-constituent. It is related to the transfer of energy ν = E-E' and the transfer of 4-momentum $Q^2 = (k-k')^2$ from the projectile to the target by basic kinematics (neglecting terms with the proton rest mass M) by $x = Q^2 \cdot (2M\nu)^{-1}$ and is thus determined from the directly measured quantities Q^2 and ν. While Q^2 constitutes the parameter which controls the spatial resolution, x controls the dynamics.

magnet defects or mechanical vibrations enhance the diffusion. Mechanical vibrations of the IR magnets of more than a few μm are not tolerable. Cultural noise has been observed to have an impact on backgrounds. The beam-beam limit of HERA occurs if the lepton beam tune spread overlaps with major resonances. The corresponding coherent motion leads to dramatic emittance growth of the proton beam emittance. This effect has been reproduced by simulations [17]. The lepton tune working space is limited by strong 2^{nd} and 3^{rd} order synchro-betatron resonances. The resonance widths can be controlled by suppressing any orbit oscillations to a level of 0.3mm with a slow orbit feedback [18] and by compensation of higher-order chromatic effects [19]. Strong synchrotron radiation (20kW) in each interaction region, which is due to the magnetic separation of lepton and proton beams, generates considerable gas desorption and critical vacuum conditions. The desorbed gas particles become targets for the protons in the IR which causes critical background conditions. This is overcome by beam cleaning of the IR vacuum system, and good pumping in the IR, in particular also for high Z molecules such as Argon. Sufficient pumping is achieved by a combination of ion pumps, NEG pumps, Ti sublimation pumps, and pumping provided by the cold beam pipe of the superconducting separator magnets. Longitudinal spin polarization of the lepton beam is obtained by spin rotator magnets around the IR-s, by spin transparent optics [20], by careful adjustment of the beam energy and by cancellation of detrimental harmonic content of spurious dipole errors [21]. The polarization with three pairs of spin rotators reaches (50-60) % [22]. Colliding particles suffer a loss of (10-20) % of polarization. Optimum tunes for high luminosity conflict with high polarization and vice versa.

The HERA ep collider is presently operated with 920 GeV protons and 27.5 GeV electrons. The record peak luminosity is $L_{peak} = 5.1 \cdot 10^{31} cm^{-2} s^{-1}$ and the average luminosity production is $\approx 1\ pb^{-1} d^{-1}$. Recent improvements include successful implementation and test of a broadband longitudinal damper system for the protons which provides proton bunch lengths of 12cm by suppressing coupled bunch instabilities [23]. As a further improvement it is planned to provide a fast orbit feedback for the leptons which is designed to reduce orbit oscillations with frequencies of up to 100 Hz to the 1 μm level at the IP. This is expected to be installed and tested in July 2006. The most important operating parameters are presented in Table 1. Figure 1 shows the HERA luminosity production in 2004-2006. After running with electrons since November 2004, positron operation will resume in July 2006. The potential for further luminosity increases at HERA amounts to 25%. Before the end of the HERA operation in June 2007, it is planned to operate HERA for three months with lower proton energy of 460 GeV for a luminosity of 10 pb^{-1}.

Table 1: HERA Parameters in 2006.

Parameter [Unit]	**Electrons**	**Protons**
Beam Energy [GeV]	27.5	920
Particles per bunch [10^{10}]	≤ 3.68	≤8.75
Number of Bunches	156	150
Horiz./vert. Emittance [nm]	20 / 3	3.8 / 3.8
Bunch length [cm]	0.9	12
Horiz./vert. β-function at IP [m]	0.62/0.26	0.18/2.45
Beam Lifetime in collision [h]	10-15	200
Longitudinal Polarization [%]	30-45	-
Peak Luminosity [$10^{31} cm^{-2} s^{-1}$]	3-5	
Average Luminosity [$pb^{-1} d^{-1}$]	1-2.5	

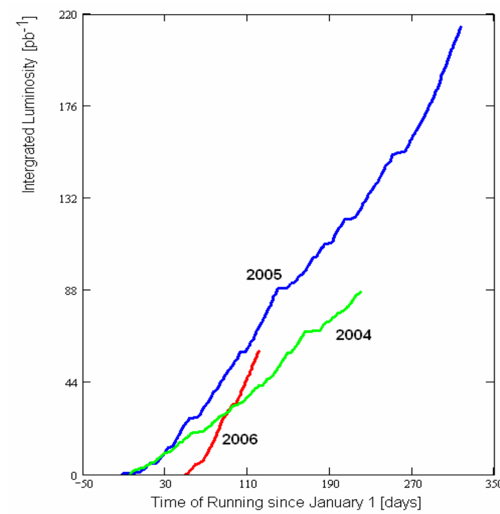

Figure 1: HERA luminosity accumulation 2004-2006.

SELECTED HERA PHYSICS RESULTS

The HERA physics program started with a spectacular success. With a delivered luminosity of only 60nb^{-1} in 1992, the total cross section of inelastically scattered 27.5 GeV electrons on 820 GeV protons plotted versus x revealed a dramatic increase of the density of proton constituents for x below 0.01 as shown in Figure 2 together with the data obtained by fixed target experiments (x > 0.01) for comparison. These results form

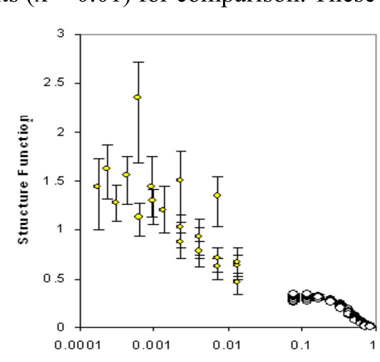

Figure 2: First measurement of ep scattering cross section versus x at HERA [24] including results of ref [4].

the basis of our present understanding of the structure of the proton with a very large density of sea quarks and gluons which make up the 99% of the proton mass. Figure 3 summarizes the HERA measurements of the proton structure function F_2 versus Q^2 for fixed values of x. These measurements constitute the synopsis of the present understanding of the proton structure. The data reveal the spatial densities and the momentum distribution of quarks and gluons in the proton. The strong dependence on Q^2 (scaling violation) for small x is a consequence of short range quantum fluctuations of gluons into quark being resolved if the spatial resolution is increased.

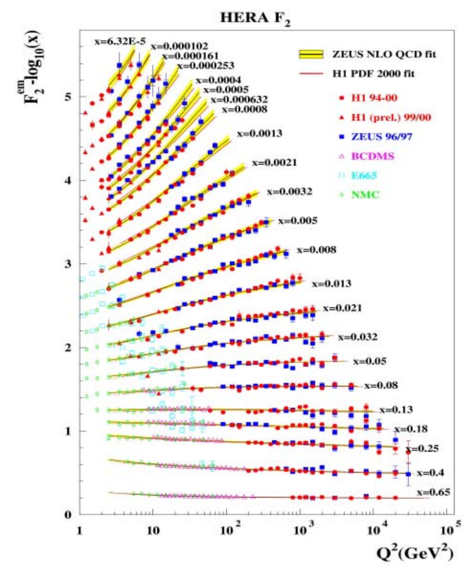

Figure 3: Proton structure function F_2 versus Q^2 in the range of $(1\text{-}10^5)$ GeV^2 for fixed values of x in the range of $0.65\text{-}6\cdot10^{-5}$ [25].

Another important part of the HERA physics program is measurements of the electro-weak interaction. According to electro-weak theory, electrons interact with quarks by exchanging either a photon, a neutral Z-boson or a charged W-boson. In ep scattering experiments, an electron is observed in the detector in the first two cases, also called neutral current events. The case of interaction via a W-boson, also called charged current is characterized by the absence of an electromagnetic shower in the detector and missing transverse momentum because of an escaping neutrino. The scattering cross sections for Z and W exchange are proportional to $(Q^2+M_{W,Z}^2c^4)^{-2}$ thus are strongly suppressed by the large Z and W masses compared to electromagnetic exchange with a cross section proportional to Q^{-4}. HERA results on this topic are summarised in figure 4. Plotted are the neutral and charged current cross sections versus Q^2 for proton electron and proton-positron scattering. All cross sections become comparable at $Q^2 \geq M_{W,Z}^2c^4$. Electron and positron cross sections for charged currents differ by a factor of two which is related to the u-d quark ratio of 2 and the helicity structure of the proton. Gamma and Z exchange interfere. This reduces the cross section in case of proton-positron neutral current events. The measurements constitute a direct experimental verification of electro-weak theory.

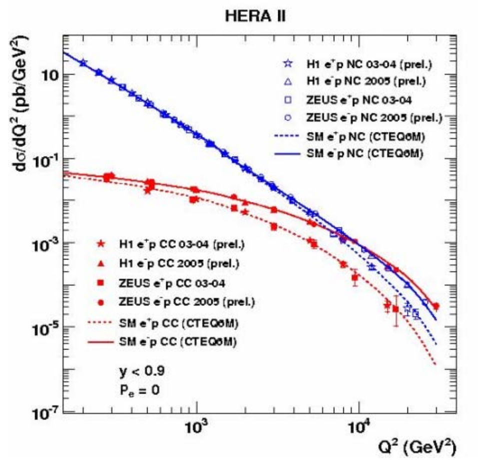

Figure 4: Charged (red) and neutral (blue) current cross sections of ep scattering at HERA [26] versus Q^2.

At HERA, the coupling constant of the strong interaction α_s was measured with high precision. It can be extracted in numerous ways from ep scattering data, for example by detecting the relative cross section of ep scattering with one or two hadronic showers. The second hadronic shower arises from a decaying gluon emitted by the struck quark which has a probability proportional to α_s. The combination of all HERA data on α_s has yielded an error of less than 1% which is a significant improvement. Figure 5 shows a plot of α_s versus the energy $\mu = 1/Q$. These data confirm the theory of asymptotic freedom, for which the Nobel Prize was awarded 2004 [29] to David Gross, David Politzer and Frank Wilczek.

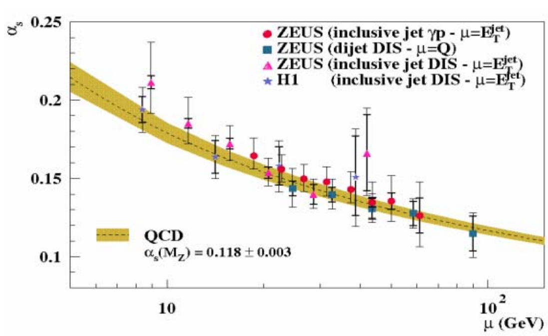

Figure 5: Measurements of α_s versus μ, the energy in the system of interacting quarks from HERA [27].

Electro-weak theory and the standard model predict that a W-boson will only couple to a left-handed electron. The polarization dependence of the charged current cross section for positrons has the opposite sign. Recent HERA data confirm these predictions with very high accuracy as shown in Figure 6 which depicts the charged current cross section for electron-proton and positron proton collisions as a function of polarization. These examples present only parts of HERA physics. Note that the important results from the non-collider, fixed target experiments HERMES and HERA-B are omitted.

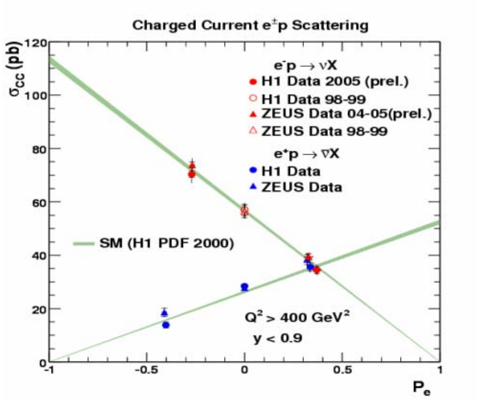

Figure 6: Measurements of the charged current cross section in HERA versus lepton beam polarization [28].

FUTURE EP COLLIDERS

The end of HERA operation in July 2007 leaves the physics program unfinished. It is most desirable to obtain further knowledge of the evolution of gluons density towards lower x. At very low values of x, the density of quarks and gluons might be so large that saturation effects might occur. In the accessible kinematic range the data do not show a hint of saturation. The investigation of the structure of the neutron is a natural complement on the physics program with protons. The study of the gluon density of nuclei with high resolution will be very important for extrapolation of quantum chromo dynamics from the perturbative into the non-perturbative domain. The symmetry of hadrons and lepton species and the exact agreement of lepton and proton charge lead to the speculation of the existence of quark-lepton resonances. The verification of this conjecture would constitute significant progress in the understanding of the nature of matter. Moreover, the results from HERA have raised a number of interesting questions which will be left unanswered due to limited kinematic range or limited statistics such as the heavy quark content of the proton. For certain parameters unexpectedly high event rates have been observed which are not explained by present theory but the statistical error is very large. For these reasons, physics on future ep colliders is considered an important part of particle physics. Examples of proposed facilities will be discussed below.

HERA III

HERA III [30] is a proposal based on HERA with a few modifications including an injector chain for the acceleration of deuterons. Two new detectors have been proposed for installation. One is specialized for electron neutron collisions while the detector acceptance of the other is specialized for the detection of low-x events to make best use of the HERA kinematic range. The HERA III physics program was rated as relevant and important by the physics community. However, due to lack of resources, no plans exist to implement these proposals.

Proton Ring-Electron Linac Colliders

The collider for ultimately expanded kinematic reach of ep collisions is based on a combination of a lepton linear accelerator with a proton storage ring. The luminosity

$$L = 4.8\times10^{30}\cdot cm^{-2}s^{-1}\,\frac{N_p}{10^{11}}\cdot\frac{10^{-6}m}{\varepsilon_p}\cdot\frac{\gamma_p}{1066}\cdot\frac{10cm}{\beta_p^*}\cdot\frac{P_e}{22.6MW}\cdot\frac{250GeV}{E_e}$$

(N_p, the number of protons per bunch; γ_p, the Lorentz factor of the protons, β_p, the proton β-function at IP, ε_{Np}, the normalized proton emittance, P_e, the electron beam power, E_e, the electron beam energy) [31], is limited by P_e and by proton emittance growth due to intra-beam scattering to values around $L=10^{31}cm^{-2}s^{-1}$. The long bunch train of a superconducting LINAC would be most favourable for such a collider as described in the THERA proposal [32]. A recent study [33] was carried out on the achievable luminosity when colliding a short train of 70GeV electrons accelerated in CLIC [34] with LHC protons combined into a 120m long super-bunch. The achievable luminosity is limited to $L=10^{31}cm^{-2}s^{-1}$. This proposal is attractive because of its synergy with the ultra high energy linear collider. A larger luminosity could be achieved by colliding a 70 GeV electron beam from a superconducting linac with the LHC protons. With P_e = 50MW, a luminosity of $3\cdot10^{32}cm^{-2}s^{-1}$ may be possible.

Ring-Ring Colliders

A recent study [35] reinvestigated the achievable luminosity of a ring-ring type ep collider based on the LHC proton beam and a new LEP-like lepton storage ring (LHeC). The aim of this study was to explore the feasibility of a very high luminosity of $10^{33}cm^{-2}s^{-1}$ with E_{cm} = 1.4TeV by optimizing the parameters around the properties of the LHC proton beam and by carrying over HERA experience. The study indicates that the ambitious performance goals are possible by introducing a 2mrad crossing angle, crab crossing for the proton beam and by developing superconducting septum quadrupole magnets.

Electron-Ion (eI) Colliders

Instead of aiming for maximum kinematic reach, concepts are developed to achieve ep and eI collisions with a very high luminosity of up to $L= 10^{35}cm^{-2}s^{-1}$. The physics program which would profit from $E_{cm} \leq 77$ GeV and high luminosity includes precise measurement of the proton structure at low-x, the measurement of spin structure functions and the exploration of the high gluon density regime (“colour glass condensate”).

Relatively low electron beam energy removes the RF power as a limiting factor for luminosity. Moreover, the use of the energy recovery linac concept (ERL), which has been successfully demonstrated at CEBAF [36] removes the issue of power consumption entirely. The luminosity of ERL-based ep colliders depends only on the beam properties and the stability of the hadron beam. Two main proposals of ERL-based ep colliders are under discussion: an upgrade of the RHIC facility at BNL, “eRHIC” [37], and an upgrade of the CEBAF facility at TJLAB, “ELIC” [38].

Both designs rely on electron cooling of the hadron beam to shape and control the hadron beam emittances in three dimensions for ultra-high luminosities. For eRHIC, the non-magnetized, bunched cooler beam of up to 54 MeV with an intensity of 0.45A CW is supplied by a superconducting RF gun (SCRFG) and accelerated in a superconducting ERL linac. New SCRFG concepts for very high intensity are under development. An R&D program including a test ERL is underway at BNL to address the challenging design issues of bunched electron cooling.

Polarized lepton and hadron beams are needed for eRHIC and ELIC. The very successful polarized proton program at the BNL [39] is an excellent base for providing polarized protons and He^3 beams for eRHIC or ELIC. The generation of high intensity (0.5A) polarized electron beams using strained GaAs photo cathodes, however, are beyond present experience and represent a considerable design challenge.

The ERL linacs must be designed for large beam intensity. In the case of eRHIC, the design is based on a 2-pass ERL. The single pass beam current for a luminosity of $10^{34}cm^{-2}s^{-1}$ is 0.45A. Thus the CW beam current in the accelerating structures amounts to 1.8A. Special RF resonators are being optimized for low parasitic mode power. These cavities feature large iris apertures and a well optimized shape to control the maximum-to-average field ratio to values around two.

Several options for eRHIC and ELIC are pursued in parallel. The most ambitious eRHIC version uses the RHIC tunnel for the ERL vertically stacked recirculation magnets. This design for $10^{34}cm^{-2}s^{-1}$ offers the possibility of four interaction points and would allow parallel hadron-hadron and hadron-ion operation. The ELIC concept includes two figure-8 shaped rings, one for acceleration of polarized hadrons with zero spin tune and one for lepton beam circulation. Electrons are circulated for 100 turns before the beam is re-injected into the ERL for energy extraction. The present design includes a flat beam and a large crossing angle of 100mrad at the four IPs which is compensated by crab crossing. Table 2 compares the most ambitious ep scenarios of the two proposals.

Table 2: eRHIC and ELIC Main Parameters.

	eRHIC p/e		ELIC p/e	
Beam Energy [GeV]	250	10	150	7
Particles/bunch [10^{11}]	2	1	0.04	0.1
Bunch frequency [MHz]	28		1563	
Beta function at IP [cm]	26	30	0.5	0.5
Normal. Emittance [µm]	2.4	5	1/0.04	100/4
Bunch length [cm]	20	0.09	0.5	0.5
Luminosity [10^{33} $cm^{-2}s^{-1}$]	9		77	

CONCLUSIONS

Lepton hadron colliders have provided important information on nature of matter. With the end of HERA running in sight, a large and strong community of physicist is looking forward for a continuation of the physics program with colliding leptons and hadrons as a necessary complement of the physics of proton-proton and electron-positron collisions. Accelerator scientists have taken up the challenge to overcome the HERA limitations in luminosity and kinematic range.

REFERENCES

[1] E.E. Chambers, R. Hofstadter, Phys. Rev. 103, 1454 (1956).
[2] J.I. Friedman, 14th Int. Natl. Conf. HEP, Vienna (1968)
[3] E.D. Bloom et al, SLAC PUB 796 (1968)
[4] See for example L.W. Whitlow, Thesis, SLAC-357(1990)
[5] HERA proposal, DESY (1981)
[6] U. Schneekloth (ed), DESY HERA 98-05 (1998)
[7] A. Sokolov, I. Ternov, Sov. Phys. Dokl.8,1203(1964)
[8] J. Buon, K. Steffen, Nucl.Inst.Meth., A245, 248 (1986)
[9] F. Willeke, F. Zimmermann,PAC91, San Fran.(1991)
[10] O. Brüning et al, DESY HERA 95-05 (1994)
[11] S. Brinker et al, this conference, THPCH083
[12] S. Herb, Kerntechnik, Carl Hanser, 1991.
[13] E. Metral et al, EPAC02, Paris (2002), p.1535
[14] D. Heins et al, EPAC96, Sitges (1996) p1857
[15] Mike Seidel, PhD Thesis, Univ.Hamburg (1992)
[16] P. Hahne, E. Lohrmann, DESY-HERA 87-26 (1987)
[17] J. Shi, PAC03, Portland (2003), WOAA009
[18] J. Keil et al, this conference, THPCH086
[19] F. Willeke, EPAC04, Luzern (2004), MOPLT046
[20] A. Chao, K.Yokoya, KEK TRISTAN Report 81-7 (1981)
[21] E. Gianfelice-Wendt, EPAC94, London (1994),p.184
[22] D.P. Barber et al, EPAC2004, Luzern, (2004),
[23] M. Hoffmann et al, this conference, THPCH085
[24] Replotted from Abt et al Nucl.Phys. B407 (1993) 515
[25] H1 and ZEUS preliminary
[26] H1 and ZEUS preliminary
[27] H1 and ZEUS preliminary
[28] H1 and ZEUS preliminary
[29] nobelprize.org/physics/laureates/2004/public.html
[30] HERA III Letter of intend, DESY 2003
[31] M. Tigner, B. Wiik, F. Willeke, PAC91, San Francisco (1991), p.2910
[32] TESLA TDR VI, p99ff, DESY 2001-11
[33] D. Schulte, F. Zimmermann, EPAC04, Luzern (2004), MOPLT039
[34] clic-study.web.cern.ch/CLIC-Study/
[35] J. Dainton et al , this conference
[36] L.Merminga, D.Douglas, G.Krafft Ann. Rev. of Nucl. and Part. Sci. 53 387 (2003)
[37] V.N. Litvenko et al, PAC05, Knoxville (2005), p2768
[38] Ya. Derbenev et al, PAC05, Knoxville (2005), p1437
[39] www.bnl.gov/bnlweb/pubaf/pr/2001/bnlpr121701.htm