Options and implications for ep experiments at HERA and beyond

Carsten Niebuhr [a]

[a]DESY
Notkestrasse 85
22607 Hamburg

At the *ep* collider HERA 920 GeV protons collide with 27.5 GeV electrons or positrons. Until the year 2000 a luminosity of $\approx 180\text{pb}^{-1}$ has been delivered to the two experiments H1 and ZEUS. A further substantial step in luminosity is expected from an luminosity upgrade which has been performed at HERA in 2001. A fourfold increase of the instantaneous luminosity should enable the experiments H1 and ZEUS to collect $\approx 1\text{fb}^{-1}$ until the end of 2006. Furthermore the installation of spin rotators will allow studies of polarised $\vec{e}p$ scattering. In order to fully exploit the upgraded machine extensive detector upgrades were performed emphazising enhanced trigger and tracking capabilities. Various possibilities for future lepton-hadron colliders based on existing facilities like HERA or RHIC are presently being discussed. They include options for polarised protons, deuterons and heavier nuclei.

1. Introduction

Lepton-hadron scattering has contributed significantly to our present understanding of the structure of matter. The continuation of fixed-target deep inelastic scattering (DIS) experiments to the high-energy lepton-hadron collider HERA at DESY has extended our knowledge of structure functions to previously unexplored parameter regions of Bjorken-x and Q^2. Using the point-like electron [1] as a clean probe various aspects of QCD can be studied: hadron space and spin structure, the space time picture of strong interactions, confinement and understanding of constituent masses. In the region of highest x- and Q^2-values sensitive tests of electro-weak physics and of physics beyond the Standard Model can be made with an integrated luminosity of 1 fb^{-1}. In order to reach this goal until the end of 2006 a luminosity upgrade of HERA was made in 2001. Polarisation of both beams, accelerating ions instead of protons and increasing the available center-of-mass energy offer very attractive possibilities for a continuation of this physics programme. For all of these options technical realizations seem possible and are being investigated.

[1]Electrons or positrons can be stored in HERA. Here and in what follows electron stands for both electrons and positrons.

2. The *ep* Collider HERA

At HERA 27.5 GeV electrons collide with 920 GeV protons . Since the start of HERA operation in 1992 a steady increase of integrated luminosity per year was reached (fig. 1) by improving the overall run efficiency and increasing beam currents. In the year 2000 the design value of $\mathcal{L} = 1.5 \cdot 10^{31}\text{cm}^{-2}\text{s}^{-1}$ was routinely surpassed at the start of a luminosity fill. However for a substantial further increase larger modifications of the interaction regions were unavoidable.

2.1. HERA Luminosity Upgrade

For equal vertical and horizontal proton emittances $\varepsilon_x = \varepsilon_y$ the luminosity at HERA is given by:

$$\mathcal{L} = \frac{\gamma_p}{4\pi e} \cdot \frac{N_p}{\varepsilon_N} \cdot I_e \cdot \frac{1}{\sqrt{\beta^*_{p,y}\beta^*_{p,x}}} \qquad (1)$$

Therefore three different possibilities exist to increase the luminosity:

- increase the proton brightness $\frac{N_p}{\epsilon_N}$
- increase the e beam current I_e

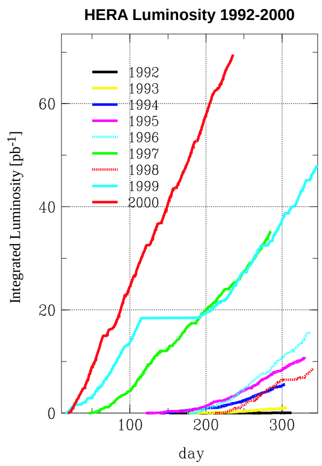

Figure 1. Integrated luminosity produced at HERA in the years 1992-2000.

- decrease the p beta function at the interaction point β_p^*

While there are no fundamental limitations for any of these options decreasing the β-function at the IP was chosen for the HERA luminosity upgrade as it was considered to be the safest method.

At the same time spin-rotators have been installed which will allow to have longitudinally polarized electrons for H1 and ZEUS. Details are described elsewhere in these procedings [1].

2.2. Principle of the new Interaction Region

In the old focussing scheme the first proton quadrupole was at a distance of 26 m from the interaction point (IP). In order to focus the proton beam stronger these magnets had to be moved closer to the experiments requiring an earlier magnetic separation of the electron and the proton beam. The new machine lattice around the IP is shown in figure 2a. Key elements are:

- GM magnets: new septum proton quadrupoles at ± 11 m from the IP. A very thin mirror plate allows protons to be focussed without large disturbance on the electron beam which is only ~ 7 cm away.
- two combined function magnets GO and GG inside the experiments.

Very tight space constraints especially inside the H1-LAr calorimeter cryostat required a superconducting design for GO and GG (fig. 3). These magnets have been designed and constructed at Brookhaven National Laboratory. In addition 2×27 new warm magnets have been built at the Efremov Institute in St. Petersburg and were installed in the regions ± 70 m around the IPs.

The reduction of the e beam bending radius from 1200 m to 400 m results in a significantly increased power of synchrotron radiation with critical energies up to 150 keV. At the design current of 58 mA electron current a total power of 28 kW will be produced which has to pass through the interaction region and has to be absorbed at absorbers placed at 11, 19 and 25 m behind the experiments. Figure 2b shows a blow up of the region around the H1 detector. In order to leave space for the synchrotron radiation fan the shape of the new beam pipe is elliptical (46 [64] mm (ver.) $\times 119$ [129] mm (hor.) in the case of ZEUS [H1]). The central part of the beam pipe is made out of 2 mm aluminum-beryllium alloy (AlBeMet AM162, Be 62 %, Al 38 %) because of its excellent mechanical properties and long radiation length. Integrated tungsten collimators shield the inner detector elements and the beam pipe from synchrotron radiation which is backscattered from the downstream absorbers. In table 1 the relevant machine parameters before and after the upgrade are compared. The combined effect of the reduced β-function at the IP and somewhat increased beam currents will lead to a luminosity of 7×10^{31} cm^{-2}s^{-1} which is more than a factor of four higher than before the upgrade.

3. H1 and ZEUS upgrades

The installation of the new superconducting magnets together with the new elliptical beam pipe in the experiments entails necessary modifications of inner detector components of H1 and ZEUS.

Due to the significantly increased load from synchrotron radiation hitting the photon detec-

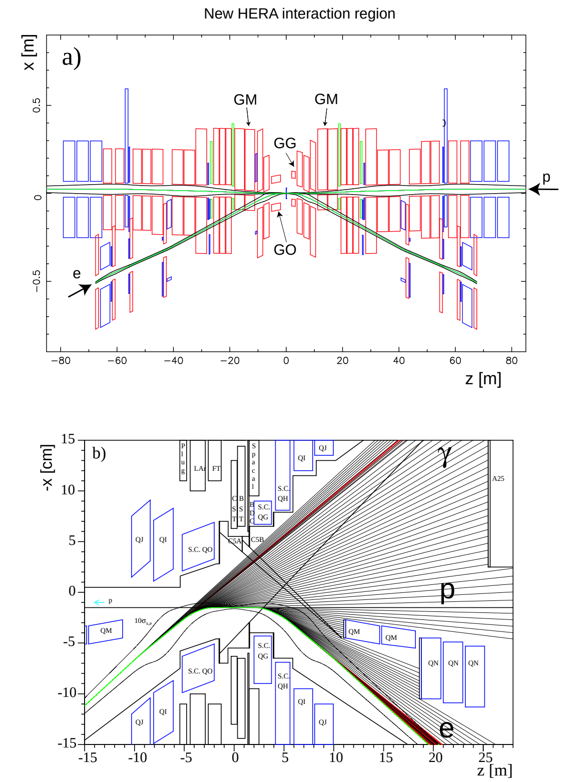

Figure 2. a) Layout of the modified interaction region. b) Synchrotron radiation produced inside the experiments has to pass the detector through the elliptical beam pipe.

Figure 3. The 3.20 m long GO magnet attached to the beam pipe before insertion into the LAr cryostat of the H1 detector.

Table 1
Comparison of machine parameters before and after the luminosity upgrade.

Parameter	before upgrade		after upgrade	
	e-ring	p-ring	e-ring	p-ring
E [GeV]	27.5	920	27.5	920
I [mA]	50	100	58	140
β_x^* [m]	0.90	7.0	0.63	2.45
β_y^* [m]	0.60	0.5	0.26	0.18
ε_x [nm]	41	$5000/\gamma$	22	$5000/\gamma$
$\varepsilon_y/\varepsilon_x$	10%	1	18%	1
σ_x [μm]	190	190	120	120
σ_y [μm]	50	50	30	30
$\Delta\nu_x$	0.012	0.0013	0.027	0.002
$\Delta\nu_y$	0.03	0.00035	0.041	0.0005
$\mathcal{L}$	1.5×10^{31}		7×10^{31}	

tors of the luminosity systems and due to the larger probability of bunch to bunch pile up a complete rebuilding of these systems for H1 and ZEUS was mandatory. The details of these new systems are described elsewhere in these proceedings [2,3].

Furthermore, in order to fully benefit from the increased instantaneous luminosity a number of additional upgrades have been performed in both experiments. The emphasis was placed on improved tracking and triggering capabilities.

3.1. Tracking

To increase the acceptance for high-Q^2 high-x (high-mass) states tracking in the forward [2] region of the detectors was improved. In addition tagging and reconstructing of heavy-flavour particles by recognition of displaced vertices will greatly improve by extention (H1) and introduction (ZEUS) of silicon vertex detectors.

[2] At HERA forward (backward) means in the direction of the incoming proton (electron) beam.

3.1.1. Forward Tracking Upgrades

Track finding in the forward direction is complicated at HERA due to large background close to the beam pipe and high track densities from showers and jets. In the pre-upgrade configuration both H1 and ZEUS operated transition radiation detectors (TRD) in the forward direction for e/π separation in the momentum interval $1-30$ GeV. In both experiments these TRDs now have been replaced by robust and well understood tracking devices for the benefit of an increased tracking redundancy.

ZEUS Straw Tube Tracker: In the new setup ZEUS operates two new modules of straw tube trackers which are interleaved with the existing three sets of planar drift chamber modules. Each of the new modules consists of four super layers of straws as shown in fig. 4.

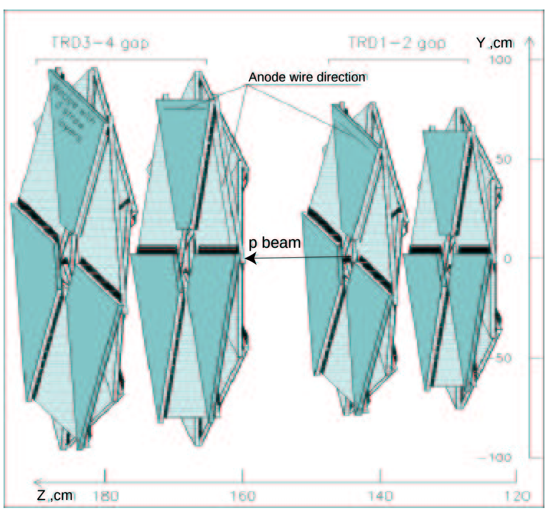

Figure 4. Arrangement of four super layers per module.

New H1 Forward Planar Chambers: In the case of H1 TRDs and Radial drift chambers were replaced by in total five new planar drift chambers each with 8 wires strung perpendicular to the beam axis. Including the existing planar drift chambers up to 76 measurement points can be obtained for tracks going in the forward direction.

3.1.2. Silicon Vertex Detector Upgrades

At H1 silicon strip detectors in the central (CST [4]) and in the backward (BST [5]) region are in operation since 1997. Several upgrades to this system were made:

- adaptation to the new beam pipe geometry
- completion of BST pad detector
- new radiation hard readout electronics for CST
- instrumentation of forward region with silicon planes: FST

The new geometry of the H1 silicon detector is shown in fig. 5a. In the backward direction six double planes are arranged perpendicular to the beam axis (BST). Each plane consists of 12 wedge shaped, single sided, single metal silicon strip detectors with φ strips oriented in a u/v configuration (fig. 6a). The φ planes are interleaved with four planes of silicon pad detectors (fig. 6c) which allow to trigger on backwards going tracks and to reject upstream proton background.

In the central region a new ladder arrangement matching the elliptical shape of the beampipe was chosen. In two layers the sensors are placed perpendicular to rays originating from the IP which is shifted in the $x-$direction wrt the center of the beam pipe (fig. 5c). During a period of machine studies at the end of 1998 the inner layer of the CST received a radiation dose of ≈ 250 Gy. This led to a significant radiation damage of the readout electronics caused by an internal leakage current in the analog pipeline readout chip (APC128) [6]. As a consequence the ASIC design of this chip was transferred from SACMOS to radiation hard DMILL technology. It was possible to re-use the old silicon sensors.

In the forward direction tracking is further improved by adding a new set of five φ-planes and two r-planes (with strips at constant radius for improved pattern recognition, see fig. 6b). As for the BST four sensors are left out in each plane of the FST to leave space for the elliptical beampipe (fig. 5b). Altogether the H1 silicon trackers cover polar angles in the range $7^o - 173^o$.

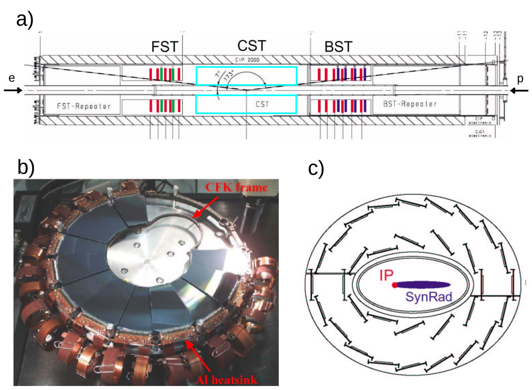

Figure 5. Layout of the H1 silicon vertex detector along (top) and perpendicular to the beam line (bottom).

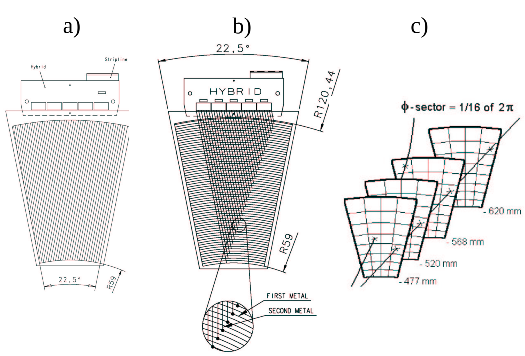

Figure 6. Schematics of the readout structure of BST and FST sensors.

In the framework of the HERA upgrade ZEUS constructed a new micro vertex detector (MVD) [7,8] with the following design goals:

- provide three spatial measurements per track in two projections
- polar angle coverage $7^o - 160^o$
- $< 20\mu$m hit resolution for normal incidence
- impact parameter resolution of $\approx 100\mu$m for $p > 2$ GeV

Constraints are given by the size and shape of the beampipe and the inner diameter of the ZEUS central tracking chamber (CTD) of 320 mm. The resulting setup is shown in fig. 7. The barrel section (BMVD) is about 65 cm long and consists of three layers of silicon strip sensors arranged in three planes surrounding the beamline. Each layer consists of two planes of single sided silicon strips. The strip pitch is 20μm but only every 6th strip is AC coupled to an aluminium readout line. The required resolution of < 20 μm is then obtained by capacitive charge sharing between the strips. In the barrel section two sensors are glued together (fig. 8a) and one sensor is electrically connected to the other via a copper trace etched on a 50μm thick polyimid foil. Five BMVD modules are mounted on a carbon fibre ladder which provides mechanical stability and cooling for the readout chips.

The forward section consists of four wheels, each of them made of two layers of 14 silicon sensors of the same type as used for the barrel section but with a trapezoidal shape. In each wheel strips of the two layers are tilted by $180^o/14$ with respect to each other (fig. 8b).

The detector signals are read out with the Helix 3.0 chip [9] which has 128 input channels and a 128 event deep pipeline. In total 2.9 m^2 of silicon of silicon are used corresponding to 207.000 readout channels.

3.2. Triggering

In order to cope with the expected higher event rates after the luminosity upgrade modifications were required also for the trigger systems of the experiments. A number of upgrade projects based on state of the art electronics have been implemented which will provide better background rejection capabilities and higher selectivity for specific final state topologies.

New z-vertex Trigger (H1): To increase robustness against severe background conditions H1 has replaced its double layer central inner multiwire proportional chamber (CIP) by a chamber

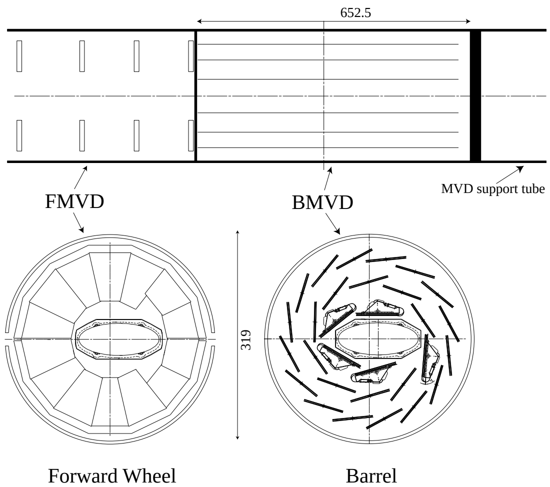

Figure 7. Layout of the ZEUS micro vertex detector along (top) and perpendicular to the beam line (bottom).

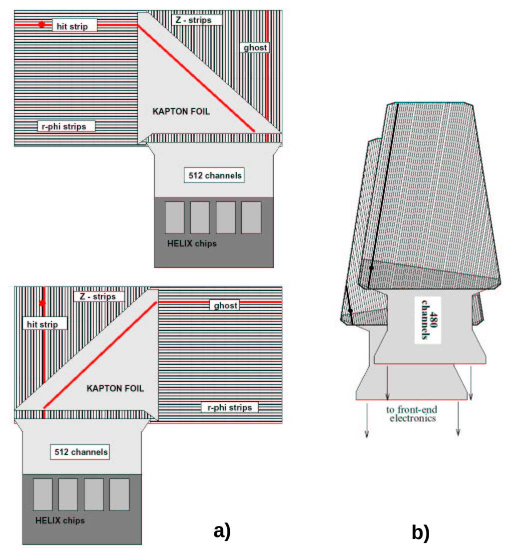

Figure 8. Schematic of readout cells for a) the barrel part (BMVD) and b) the forward part (FMVD) of the ZEUS micro vertex detector.

with five layers. As in the old CIP one cathode of each layer is divided into pads segmented in φ and along the beam axis but with a much finer granularity leading to a $\sim$ 10 fold increase in total number of pads. In order to provide a level one (L1, 2.3μs) trigger signal based on a z-vertex histogramming technique these 9600 pads have to be read out via optical link modules at a data rate of 4×832 Mbps within the HERA bunch crossing time of 96 ns [10]. The tight spatial constraints for the on-detector electronics are particularly challenging.

Jet Trigger (H1): The concept of this trigger is based on the search for localized energy depositions ("jets") in the H1-LAr calorimeter. The jets are obtained from digitally summed trigger towers at a finer granularity (factor of four) as done previously. As a result the digital trigger thresholds can be lowered. The jet quantities and the higher granularity trigger towers will also be made available for more complex trigger decisions at trigger level two (L2, 23μs) involving additional detector components.

Fast Track Trigger (H1): The Fast Track Trigger (FTT) [11] uses hit information from 4 wire groups of the central jet chamber (CJC) of H1 (fig. 9a). It will be integrated in the first three levels (L1-L3) of the H1 trigger scheme to provide higher selectivity for events with charged particles. The FTT will allow to reconstruct 3-dimensional tracks in the CJC with $p_t \geq$ 100 MeV/c within the L2 latency of 23μs. To reach the necessary momentum resolution of $\sim$ 5% (at 1 GeV/c) sophisticated reconstruction algorithms have been implemented using high density Field Programmable Gate Arrays (FPGA) and their embedded Content Addressable Memories (CAM). The final track parameter optimization is done using non-iterative fits implemented in DSPs. While at the first trigger level rough track information will be provided, at L2 tracks with high resolution are available to form trigger decisions on topological and other track based criteria like multiplicities and momenta. At the third trigger level (L3, $\sim$ 100μs) a farm of commercial processor boards will be used to compute physics quantities such as invariant masses (fig. 9b).

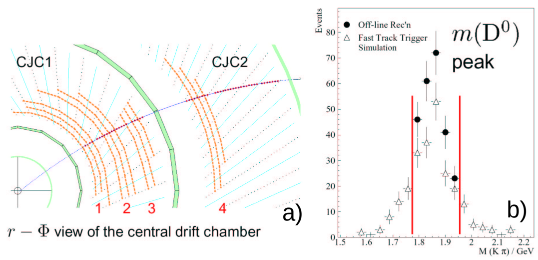

Figure 9. a) The four trigger layers of CJC used for the FTT are marked by the thick dashed lines. b) Simulated D^0 mass resolution at L3 of the FTT compared to the offline result.

Global Track Trigger (ZEUS): ZEUS has implemented a new second level trigger based on five dual-CPU PCs (processing time $\sim 10 - 15\ \mu$sec) which uses information from the new micro vertex detector (MVD), the central track detector (CTD) and the straw tube tracker (STT) in the forward direction.

4. Future Lepton-Hadron Collditers

4.1. Future options for HERA

The interest in $\vec{e}\vec{p}$ scattering with polarized electrons and protons and in eA scattering has been well documented in a series of workshops held at DESY and elsewhere [12].

Polarized Protons in HERA: Whereas polarisation of the electron beam is building up naturally by emission of spin flipping synchrotron radiation, the only feasible way of obtaining a high energy polarized proton beam presently is acceleration of polarized protons after creation in a polarized H^- source. Encouraging results have been obtained at RHIC in January 2002 when for the first time polarized protons have been stored, accelerated to 100 GeV and brought to collision. As at RHIC depolarizing resonance effects during acceleration would have to be avoided at HERA by using a combination of at least four Siberian Snakes. In addition spin-rotators will be required around the experiments.

Polarized Deuterons: The small gyromagnetic moment of the deuteron ($G_d = -0.14$) makes preservation and manipulation of the deuteron polarization with Siberian Snakes impractical. On the other hand novel approaches are being discussed in which spin flips are achieved by applying horizontal rf fields [13]. Moreover the smallness of G_d means that depolarizing resonances are much weaker and further apart than for protons. This makes electron-deuteron scattering a very attractive option for a future HERA programme as no big modifications of the machine are required.

Ions in HERA: For acceleration of ions with $A > 2$ in HERA a new LINAC would be required [14]. However the largest problem with ions in HERA is intra beam scattering (IBS) which limits the beam lifetime. In order to reach luminosities which scale like $\mathcal{L}_A \simeq \mathcal{L}_p/A$ electron beam cooling seems unavoidable to balance the effect of IBS. Studies indicate that a scheme in which precooling in PETRA is followed by cooling in HERA would be optimal.

4.2. Electron Ion Collider

Recently the idea for an intense polarized electron-ion collider (EIC) using electron beam cooled ions in RHIC ($E_p \leq 250$ GeV or $E_{Au} \leq 100$ GeV$/u$) colliding with electrons from a ring or linear accelerator of about 10 GeV maximun energy was put forward [15]. Although the EIC has $\mathcal{O}(10)$ times less center-of-mass energy than HERA, it greatly extends the range of current polarized fixed target experiments due to its high luminosity, and with heavy nuclei gives access to high parton densities. The ring-ring accelerator has an estimated luminosity of $25(0.7) \times 10^{31}$ cm^{-2}s^{-1} for $p(Au)$. With an energy recovery linac it is expected that even luminosities of $100(1.0) \times 10^{31}$ cm^{-2}s^{-1} for $p(Au)$ can be obtained. The linac-ring option has the additional advantage of providing high polarisation and low synchrotron radiation background.

4.3. Options for higher E_{CM}

A number of options for ep colliders at $\sqrt{s} \approx 1$ TeV are being discussed. They are based on existing and planned accelerators.

4.3.1. THERA

If the proposed e^+e^- collider TESLA would be realized at DESY a tangential arrangement with respect to the existing HERA tunnel would allow one to collide 300-920 GeV protons with $250 - 800$ GeV leptons (polarized $e^{\pm}$) reaching centre of mass energies well beyond 1 TeV [16]. Various configurations of E_e/E_p ratios ranging from 1/4 to 1 have been studied resulting in annual luminosities of 40 to 250 pb^{-1} assuming electron cooling of protons in PETRA. Depending on the choice of energies symmetric or more asymmetric detector setups are required with dimensions similar to the existing HERA detectors. Fig. 10 compares the accessible kinematic range in x and Q^2 for THERA with HERA and EIC.

4.3.2. eLHC

The option for lepton-hadron collisions in the LHC tunnel was studied in [17]. Colliding 60 GeV electrons with 7 TeV protons yields $\sqrt{s} \approx 1.3$ GeV. Assuming average beam currents of 180 mA (e) and 123 mA (p) a luminosity of $2.5 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$ could be reached.

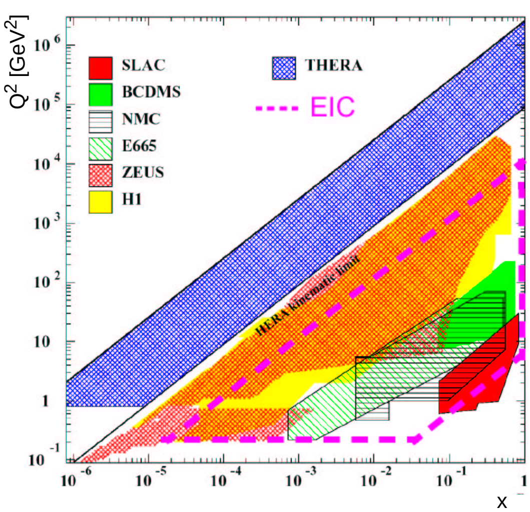

Figure 10. Physics range covered by HERA, EIC and THERA in x and Q^2.

REFERENCES

1. T. Behnke, K. Long "Polarization measurements at $e^{\pm}$-beams", *These proc.*
2. U. Koetz, U. Schneekloth "The Upgraded ZEUS Luminosity Monitor", *These proc.*
3. A. Specka "The New H1 Luminosity System for HERA II", *These proc.*
4. D. Pitzl *et al.*, Nucl. Instrum. Meth. A **454**, 334 (2000) [arXiv:hep-ex/0002044].
5. W. Eick *et al.*, Nucl. Instrum. Meth. A **386** (1997) 81.
6. M. Hilgers and R. Horisberger, arXiv:hep-ex/0101023.
7. V. Chiochia [ZEUS MVD Group], arXiv:hep-ex/0111061.
8. E. N. Koffeman [ZEUS Collaboration], Nucl. Instrum. Meth. A **473** (2001) 26.
9. M. Feuerstack-Raible *et al.*, *Prepared for 2nd Workshop on Electronics for LHC Experiments, Balatonfured, Hungary, 23-27 Sep 1996.*
10. M. Urban *et al.*, *Prepared for 6th Workshop on Electronic for LHC Experiments, Cracow, Poland, 11-15 Sep 2000.*
11. A. Baird *et al.*, IEEE Trans. Nucl. Sci. **48** (2001) 1276 [arXiv:hep-ex/0104010].
12. "Physics with HERA as eA collider" Workshop 25-26 May 1999 at DESY http://www.desy.de/heraea
"Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities" Workshop 17-20 May 1999 http://www.desy.de/heraspin/
"IPPP Workshop on Future Physics at HERA" 6-7 Dec 2001 Grey College, Durham
13. Y. S. Derbenev and V. A. Anferov, arXiv:physics/0003104.
14. G.H. Hoffstaetter, *Prepared for EPAC 2000, Vienna (June 2000)*
15. Whitepaper: The EIC Collider, http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/Whitepaper/Final/
16. The THERA book, http://www.ifh.de/thera/tbook/
17. E. Keil, LHC Project Report 93 (1997)