# OVERVIEW OF ASYMMETRIC ELECTRON HADRON COLLIDERS*

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*Abstract*

The first lepton-proton collider HERA at DESY completed its operation in 2007. Presently, several accelerator proposals for future electron-hadron colliders are under consideration in several laboratories from all over the world. The future accelerators intend to exceed the HERA luminosity by 2-3 orders of magnitude, as well as to cover the different ranges of center-of-mass collision energies. The research capabilities will be extended by including the collisions of electrons with heavy ions, as well as, in some designs, with polarized protons and polarized ions. The future electron-hadron colliders would serve as high-resolution femtoscopes able to reveal unprecedented details of the structure of nucleons and ions, including their spin content and the state of high gluon density matter. The colliders will provide us with ultimate tools to test both the ways Quantum Chromodynamics works as well as to look for new physics beyond the Standard Model. All proposed electron-hadron colliders are based on the extension of existing accelerators to accommodate the electron-hadron collisions. Advanced accelerator technologies are utilized in order to achieve the desired high luminosity.

## INTRODUCTION

The lepton-nucleon scattering has been a crucial tool of the scientific exploration for many years. The Deep Inelastic Scattering (DIS) experiments led to rise up of the quark-parton description of the nucleon structure and, ultimately, to the appearance of Quantum Chromodynamics (QCD) theory. Later experiments used the beam of the muons, electrons and neutrinos scattered on fixed targets to look at the details of the internal structure of the protons and neutrons, including their spin structure. The lepton-proton HERA collider in DESY (Germany), which operated from 1991 to 2007, brought the DIS experiments to the region of very high center-mass energy (CME) and produced remarkable physics output on the fine details of the proton structure, the discovery of very high density of sea quarks and gluons present in the proton, the detailed data on electro-weak electron-quark interactions and the precise measurement of strong interaction coupling constant [1]. In the present time there are several designs of future electron-hadron colliders under consideration in USA and Europe. Employing advanced accelerator technologies those future accelerators hope to exceed the luminosity of HERA collider by 2-3 orders of magnitude. In addition, the future electron-hadron colliders will provide the new exploration capabilities by involving electron collisions with heavy ions as well as with polarized protons and polarized light ions. Also new colliders will operate in different from HERA the center-of-mass energy (CME) regions. Table 1 lists the designed colliders together with their CMEs. All designs can be separated in two groups (Ring-Ring and Linac-Ring), according to which acceleration technique is used for the electron beam acceleration (circular accelerator or linac). The Linac-Ring designs utilize the energy recovery linacs in order to produce the high luminosity in CW mode.

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Table 1: Designed Electron-Hadron Colliders

| | Ring-Ring | | | Linac-Ring | |
|---|---|---|---|---|---|
| | ENC | MEIC | LHeC RR | LHeC LR | eRHIC |
| CME, GeV | 14 | 15-65 (140) | 1300 | 1300 (2000) | 45-175 |
| On the base of | HESR FAIR (GSI) | CEBAF (JLab) | LHC (CERN) | LHC (CERN) | RHIC (BNL) |

Table 2 presents a summary of main beam parameters for electron-proton collisions for the future collider designs discussed in this paper as well as for HERA.

## PHYSICS OBJECTIVES

Here I list some of most important studies that can be done with the future electron-hadron colliders (which are also often called electron-ion colliders, or EICs)

While, from previous experiments, the rich information has been obtained on the momentum structure functions of nucleon constituents, a high-luminosity EIC will be able to explore also the spatial distributions of nucleon constituents, thus realizing the imaging of the nucleons.

The question how the proton gets its spin remains still unanswered. This proton spin puzzle needs to be fully resolved. With EIC's, using polarized proton and electron beams, the contribution from gluons to the proton spin can be measured in the region of low momentum fraction not accessible by RHIC polarized proton experiments. The contribution to the proton spin from the orbital momentum of quark and gluons also can be obtained on the basis of the data from the proton imaging. The beams of polarized light ions will be used in EICs to get measurements for the spin of neutron.

One of the important results from HERA was the discovery of increasing gluon density at low values of gluon momentum. Mapping the gluon content of the ions and protons at low momentum region, verifying whether it is saturated at some level, and exploring the properties of this high-density gluon state are important tasks for understanding both the nucleon structure and the general ways QCD works. More efficiently the high-density gluon studies can be done with heavy ion beams. Because of that the use of the heavy ion beams is important feature of future EICs. Experiments with heavy ion beams will also provide further insights on spatial and momentum structure of the nucleus.

The physics objectives mentioned above mainly characterize the future EIC's as big femtoscopes for studies of the nucleon structure. But with the very high luminosity of such colliders or with very high CME (on TeV scale) one can also effectively do exploration and he searches for new physics (GUTs, lepto-quarks, Higgs physics…).

Table 2: Beam Parameters for HERA and for the Highest Luminosity e-p Designs of Future EICs

| | **HERA** | | **ENC** | | **MEIC** | | **eRHIC** | | **LHeC linac-ring** | | **LHeC ring-ring** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *p* | *e* | *p* | *e* | *p* | *e* | *p* | *e* | *p* | *e* | *p* | *e* |
| Energy, GeV | 920 | 27.5 | 15 | 3 | 60 | 5 | 250 | 20 | 7000 | 60 | 7000 | 60 |
| Bunch frequency, MHz | 10.4 | | 52 (104) | | 750 | | 14.1 | | 20 | | 40 | |
| Bunch intensity, $\times 10^{11}$ | 0.72 | 0.29 | 0.54 (0.36) | 2.3 | 0.042 | 0.25 | 2 | 0.22 | 1.7 | 0.02 | 1.7 | 0.2 |
| Beam current, mA | 100 | 40 | 450 (600) | 1900 | 500 | 3000 | 420 | 50 | 430 | 6.4 | 860 | 100 |
| Norm.rms emittance, x/y, µm | 5 | 1100/ 180 | 2.3/ 0.8 | 930/ 320 | 0.35/ 0.07 | 54/11 | 0.18 | 26.4 | 3.75 | 50 | 3.75 | 580/ 290 |
| β*, x/y, cm | 245/ 18 | 63/26 | 30 (10) | 30 | 4/0.8 | 4/0.8 | 5 | 5 | 10 | 12 | 180/ 50 | 18/1 0 |
| Beam size at IP, x/y/ µm | 112/30 | | 200/120 | | 15/3 | | 6/6 | | 7/7 | | 30/16 | |
| Bunch length, cm | 19 | 1 | 30 (20) | 10 | 1 | 0.75 | 8 | 0.2 | 8 | 0.03 | 8 | 1 |
| Polarization, % | 0 | 45 | 80 | 80 | 70 | 80 | 70 | 80 | 0 | 90 | 0 | 40 |
| Peak luminosity, $10^{33}$ cm$^{-2}$s$^{-1}$ | 0.04 | | 0.2 (0.6) | | 14.2 | | 9.7 | | 1.0 | | 1.7 | |

## COLLIDER DESIGNS

### *ENC*

The FAIR facility, which is under construction at GSI research center (Germany), will provide intense beams of ion and antiprotons for the scientific research. Relatively recently (2008) it was proposed to use the HESR of the FAIR facility to store the polarized protons and deuterons and also to construct 3.3 GeV electron circular accelerator in the HESR tunnel to provide polarize electrons [2,3]. This will open way to make the polarized p/d on polarized e collisions in the location of the PANDA detector, thus adding the Electron-Nucleon Collider (ENC) to the FAIR facility. The PANDA detector of the FAIR facility is intended for the experiments with antiprotons scattering on the internal target. But, much of the capability of PANDA detector can be used for e-p and e-d collision experiments.

The realization of the e-p collision capability will require a special interaction region. Also, the dedicated hardware to produce and accelerate polarized protons and deuterons has to be added in the injector chain and in the HESR ring. Longitudinal polarization of electrons and hadrons has to be produced in the interaction point. The electron cooler designed for the FAIR facility requirement has to be upgraded to higher electron current to satisfy the ENC demands.

As shown in Table 2, the baseline design would lead to the luminosity of 2 $10^{32}$ cm$^{-2}$ s$^{-1}$. But, more advanced interaction region design, with $\beta^*$ = 10 cm, is under consideration, which may allow to increase the ENC luminosity up to 6 $10^{32}$ cm$^{-2}$ s$^{-1}$.

Compared with other EICs designs the ENC is at somewhat earlier stage of development. But it clearly demonstrates a good opportunity to add the electron-nucleon scattering study capability to the FAIR facility.

### *MEIC*

Thomas Jefferson Laboratory in the United States develops the design of the Medium Energy Electron-Ion Collider MEIC. In Figure 1 the general layout of this collider is shown. All MEIC components fit well on the

JLab site. The 12 Gev CEBAF will be used as the polarized electron beam injector. A hadron accelerator complex and an electron storage ring, have to be constructed. All MEIC rings, including booster rings, have a novel Figure-8 shape. The main advantage of such a shape is that it allows for the acceleration of polarized deuteron beam, preserving its polarization. It also allows for a simple control of the deuteron polarization direction at the interaction points. The standard tools of the beam polarization control, like Siberian Snakes and spin rotators, are not very efficient for the polarized deuterons, because of low anomalous magnetic moment of this particle.

The large Figure-8 shape rings, with the circumference of 1340 m, are vertically stacked, and include the warm booster hadron ring, the cold hadron collider ring and the warm electron collider ring. Ion beams execute vertical excursion to the plane of the electron orbit for enabling a horizontal crossing. And the beam crossing geometry at IPs is based on the horizontal crab crossing due to flat colliding beams.

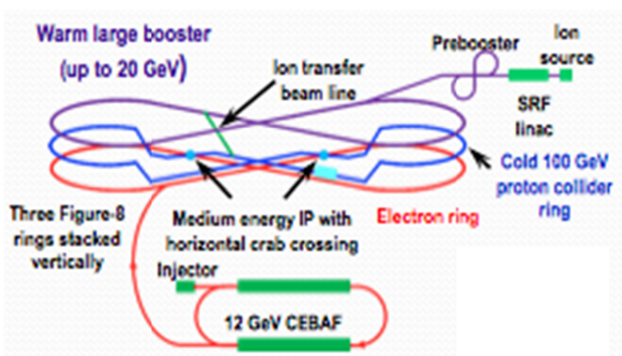


Figure 1: The MEIC layout.

MEIC intends to use the polarized electrons with the energy range of 3-11 GeV, the polarized protons with the energy range of 20-100 GeV and ions with the energy range of 12-40 GeV/u . The ions species include polarized d and $He^3$, as well as unpolarized heavy ions up to A=200.

The possibilities for the consequent upgrade of the MEIC facility to higher energy of both electrons and hadrons have been also considered. The size of the JLab site should allow such upgrade by adding a larger Figure-8 shape hadron and electron rings, corresponding to 250 GeV proton energy and 20 GeV electron energy.

Further information on the present design status of MEIC can be found in [4].

## *eRHIC*

Relativistic Heavy Ion Collider (RHIC) has been operating at BNL (USA) for more than decade, producing either polarized p-p collisions (with the proton energy up to 250 GeV) or unpolarized heavy ions collisions (with ions up to U and the ion energy up to 100 GeV/u). The future electron-ion collider eRHIC will add an electron accelerator inside the present RHIC tunnel [5].

Figure 2 shows the layout of eRHIC. The most of the electron acceleration is done by two 2.45 GeV energy-recovery linacs placed in the long 200 m straight sections of the RHIC tunnel. The six re-circulations through the ERLs lead to the electron beam acceleration up to 30 GeV. The recirculations are realized with vertically stacked recirculation passes (the beam lines), which run along the RHIC circumference. The recirculation passes are composed from compact size magnets to minimize the construction and operation costs. Highest luminosity is achieved with the electrons at (or below) 20 GeV energy. Injection system includes the high current polarized proton source and the 0.6 GeV pre-accelerator ERL. The design allows for up to 3 experimental locations where electron-ion collisions can be organized.

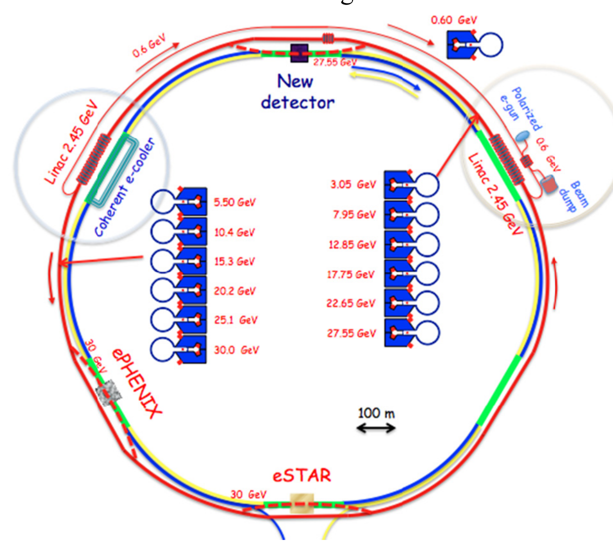


Figure 2: The eRHIC layout.

The attractive feature of the eRHIC design is that the staging of this machine can be easily arranged. It is planned that, on the first stage, eRHIC will have shorter length ERLs and the maximum electron energy of 10 GeV. On later stages the linacs will be enlarged by adding SRF cavities, ultimately reaching 30 GeV energy of electrons.

The main and pre-accelerator linacs are composed from 704 MHz SRF cavities (with 19 MV/m acceleration gradient) developed in BNL for high beam current applications [6,7]. The designs of the cavity and its cryomodule minimize and provide effective damping of the energy of cavity High-Order Modes, which is critical for a high current multi-pass ERL.

In addition, to ion species used by present RHIC, eRHIC will include also polarized $He^3$ ions.

## *LHeC*

Highest center-of-mass energy electron-hadron collider LHeC has been designed at CERN on the basis of Large Hadron Collider [8]. Two design options, linac-ring (LR) and ring-ring (RR), have been developed in parallel. LHeC aims to provide e-p collisions at the location of


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present ALICE experiment. There is an additional requirement that LHeC should be able to operate in parallel with LHC p-p collisions in other LHC interaction points. That requirement provides additional complications; for instance, for the interaction region design.

In the RR design 60 GeV electron circular accelerator is added inside the LHC tunnel, running around the circumference and bypassing with long 1.3 km bypasses the CMS and ATLAS LHC experiments.

In the baseline design of LR option a 60 GeV ERL-based accelerator is placed in the vicinity of e-p collision point, with most electron accelerator components outside of the LHC tunnel. Figure 3 shows the layout of ERL accelerator, which utilizes two 10 GeV ERLs with three e-beam recirculation scheme. Presently 721 MHz SRF cavities are considered as the basis for the linacs. The standard feature of ERL-based designs, seen in Figure 3, is strings of cavities or mini-linacs for the compensation of the energy loss caused by SR. Those compensators are done using second harmonic cavities, thus providing the energy compensation for both accelerating and decelerating beam of the energy recovery cycle.

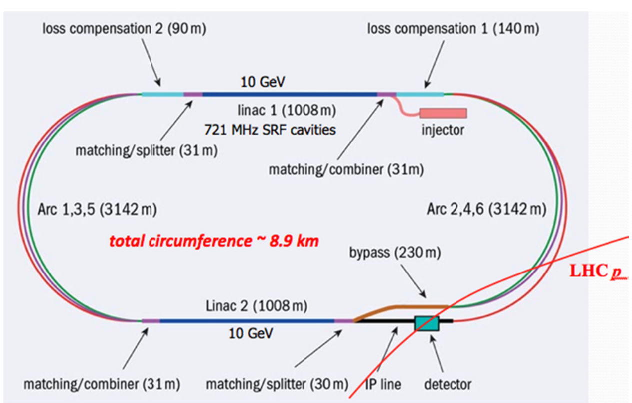

Figure 3: LHeC ERL design option layout.

Although the ERL design is the baseline for linac-ring option, the highest CME energy of 2 TeV at LHeC can be obtained with a pulsed electron linac (up to 140 GeV electron energy), but, correspondingly, with much lower luminosity.

The LHeC design includes polarized electrons but does not aim to have the polarization of the proton beam.

Comparing two design options of LHeC, one may point out that the RR design employs more conventional technology, while the LR design option has the considerable advantage of minimally affecting the LHC operation during its construction and installation.

## ACCELERATOR TECHNOLOGIES

In order to reach their luminosity and beam polarization objectives the electron-hadron colliders plan to utilize the advanced accelerator technologies.

As can be seen from the beam parameters in Table 2, for most of the future EICs the largest luminosity increase is due to smaller beam spot in the collision point. The Interaction Region design is crucial for the luminosity gains. The IR design faces the issues of strong focusing of beams at the collision point and fast separation of beams after the collision. In the same time the synchrotron radiation fan produced by electrons in the IR magnets has to be kept away from hitting the pipe inside and in the vicinity of the detectors and in superconducting magnets. Managing synchrotron radiation in the IR includes application of the collimation, absorbers and the protection masks at the appropriate locations. In Figure 4 the IR design for LHeC LR option is shown together with the SR fan. In this case, the IR has to accommodate also the third beam, protons used for the parallel LHC operation.

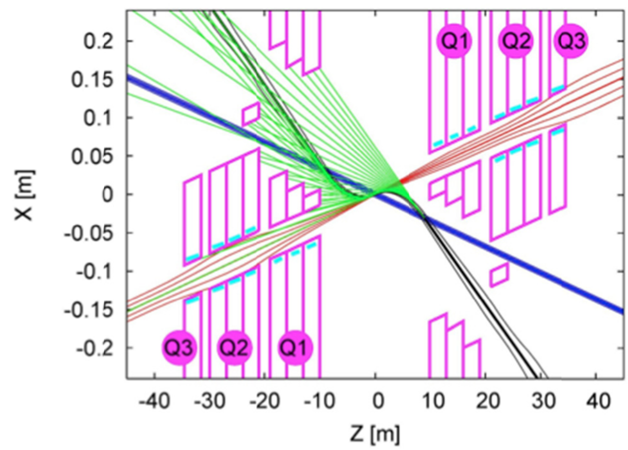

Figure 4: The IR layout of LHeC linac-ring design.

Because of the proximity of the hadron and electron beam trajectories, special designs of IR magnets have to be developed [9]. Some of superconducting IR magnet designs consider applying NbSn superconductor technology, following recent progress made for such magnets. Large crossing angle used in MEIC and eRHIC design calls for the application of crab-cavities to maximize the luminosity. Corresponding crab-cavity designs have been developed [10,11].

ENC, MEIC and eRHIC designs include the cooling of proton and ion beams. R&D for efficient cooling techniques for high energy hadrons is pursued by JLab and BNL. Novel technique of Coherent Electron Cooling (CEC) [12] aims to provide the longitudinal and transverse cooling of eRHIC proton beam on the time scale of few tens of minutes. The proof-of-principle experiment for CEC, funded by DOE NP Office of Science, is being prepared in RHIC by the collaboration of BNL, JLab and Tech-X [13]. The experiment will take place in 2014-2016. The aim of the experiment is to demonstrate the longitudinal cooling of 40 GeV/u Au beam. On the other side, MEIC intends to apply the magnetized electron cooling. The electron cooler based on a recirculator ring have to be used to provide 1.5 A of high quality electron beam with the energy up to 32 MeV. The recirculator (from 10 to100 recirculation turns) is fed by the ERL. Fast kickers, providing the injection and



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ejection of the electron bunches in/from the recirculator, have to operate with the repetition rate from few MHz to tens of MHz and 1 GHz bandwitdh. The test facility for the beam recirculator has been proposed in JLab on the basis of the FEL ERL [14]. The test facility intends to explore the beam quality lifetime of bunches in the recirculator, related beam dynamics issues, and, on second stage of the experiment, the operation of fast kickers. The present plan is to complete the first stage of the recirculator test in 2015.

For the ERL-based colliders high beam power ERL technology will be used. The ERL test facility has been built in BNL in order to test the key components of SRF technology (with a 704 MHz BNL cavity) and the energy recovery with high beam average current (up to 0.5 A) [15].

The polarized beam technologies are also in the core of EICs designs. All future colliders plan to use the polarized electron beam. In the ring-ring designs the spin matching and the harmonic correction techniques have to be employed to minimize the beam depolarization due to synchrotron radiation, especially, in the presence of spin rotators and solenoidal detector magnets [16]. On the other side, the linac-ring designs utilize the high-current polarized electron source, with the average current ranging from 6 mA (LHeC) to 50 mA (eRHIC). The development of the high current polarized gun is the important R&D item of the LR designs [17]. Most of the future EICs also plan to use the polarized proton and light ion beams. eRHIC will take advantage of the multiple devices and techniques already utilized in the injector chain, as well as in RHIC itself, for the successful acceleration of polarized protons through numerous spin resonances, and for the control of the proton polarization in the interaction points. MEIC will take advantage of the Figure-8 shaped rings to accelerate polarized deuteron beam [18].

For all future colliders the additional capability of using positron beam is very favorable. In the case of the linac-ring designs the task of achieving the luminosity of $e^+$-p collisions to be of similar order with $e^-$-p collisions presents a great challenge. In the development of LHeC LR design the novel techniques for increasing the positron beam intensity are under consideration. Those include the advanced targets for the $e^+$ production, the use of powerful gamma beam source and the schemes for positron beam recycling and reuse [19].

## ASYMMETRIC DESIGN ISSUES

Some important design features are related to the asymmetric nature of EICs colliders in terms of colliding species.

First of all, all of the collider designs take the advantage of the HERA experience, and require the matching of the electron and hadron beam sizes at the interaction point. Since MEIC and eRHIC intend to operate in a wide range of electron and hadron energies, the control of $\beta^*$ and transverse emittances of both electrons and hadrons to match the IP beam sizes at all energies is vital. This fact puts requirements on the lattice design, as well as, for the LR designs, on the electron source emittance control.

The second feature concerns the bunch frequency matching of the electrons and hadrons. For both eRHIC and MEIC the hadrons are not yet ultra-relativistic, and the change of the hadron energy considerably affects the hadron revolution frequency. Special provisions have to be made in those collider designs to match the bunch frequencies of hadrons and electrons at different hadron energies. These provisions include the variable circumference of either electron or hadron accelerators, RF harmonic switching and the appropriate range of frequency tuning for the SRF cavities.

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