FUTURE ELECTRON-HADRON COLLIDERS*

Vladimir N. Litvinenko#, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

Abstract

Outstanding research potential of electron-hadron colliders (EHC) was clearly demonstrated by first – and the only - electron-proton collider HERA (DESY, Germany) [1,2]. Physics data from HERA revealed new previously unknown facets of Quantum Chromo-Dynamics (QCD). EHC is an ultimate microscope probing QCD in its natural environment, i.e. inside the hadrons. In contrast with hadrons, electrons are elementary particles with known initial state. Hence, scattering electrons from hadrons provides a clearest pass to their secrets. It turns EHC into an ultimate machine for high precision QCD studies and opens access to rich physics with a great discovery potential: solving proton spin puzzle, observing gluon saturation [3] or physics beyond standard model [4]. Access to this physics requires high-energy high-luminosity EHCs and a wide reach in the center-of-mass (CM) energies. This paper gives a brief overview of four proposed electron-hadron colliders: ENC at GSI (Darmstadt, Germany), ELIC/MEIC at TJNAF (Newport News, VA, USA), eRHIC at BNL (Upton, NY, USA) and LHeC at CERN, Geneva, Switzerland).

I want to thanks A.Lehrach (Juelich); BNLs' eRHIC team J.Beebe-Wang, I.Ben-Zvi, X.Chang, Y.Hao, A.Jain, D.Kayran, G.Mahler, W.Meng, B.Parker, V.Ptitsyn, T.Roser, J.Skaritka, D.Trbojevic, N.Tsoupas, J.Tuozzolo, G.Wang; and O.Bruening, H.Burkhardt, R.Tomas, M.Klein, J.Jowett and F.Zimmermann from LHeC team for the information.

Y.Zhang from TJNAF provided six slides on ELIC/MEIC with specific request not to comment on their designs. Hence, in this paper I copy ELIC/MEIC parameters and descriptions from his material without any checks for self-consistency. This is neither a criticism nor an endorsement of the ELIC/MEIC design.

ELECTRON HADRON COLLIDERS

Great successes achieved by HERA stimulated intense interest in both the accelerator and the high energy and nuclear physics communities. Abilities of electron-hadron collider to provide information on nucleon structure complimentary to that obtained in hadron and lepton colliders and very high precision of its data were and are behind this interest. Presently there are three groups at BNL, CERN and GSI plan to add lepton accelerator to the existing (RHIC at BNL and LHC at CERN) or future (FAIR at GSI) hadron facilities. Fourth group at TJNAF suggest to use CEBAF facility as an injector of polarized electron into ELIC/MEIC and to build a new hadron injection complex and new lepton and hadron rings.

There is number of common features for the four colliders. All of them plan using longitudinally polarized electrons or/and positrons. At least three of them ENC, ELIC/MEIC and eRHIC plan also using polarized protons as well as polarized light ions (D, ^{3}He, etc.). ELIC/MEIC, eRHIC and LHeC plan to operate in e-A mode, i.e. collide un-polarized electrons with heavy ions (up to uranium).

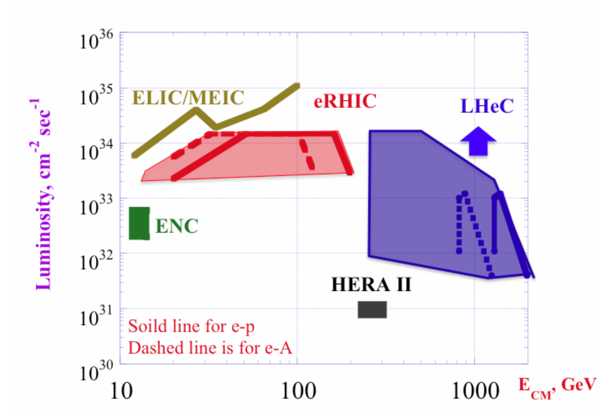

Figure 1: Luminosity and the CM energy of the Electron-Hadron Colliders. Luminosity in e-A case is per nucleon, i.e. it is the RHIC style "equivalent e-p luminosity.

One of important parameters for the physics reach of the collider is its CM energy. For e-A collisions it is the energy per electron-nucleon pair. Other very important parameter of a collider is its luminosity. Fig.1 shows these parameters for the four proposed and HERA colliders.

There are two possible scenarios for electron-hadron collider, which differ by the choice of either a ring or a linac as a driver for the electron beam. In the later case use of energy recovery linac (ERL) often provides opportunities for significantly higher luminosity. In practice, for an ERL based EHC, the limit can be set either by an available electron (positron) beam current or by a kink instability [6]. Latest studies showed that the later can be suppressed by a proper choice of chromaticity in the hadron ring or by a simple feedback [7].

Two colliders, ENC [8] and ELIC/MEIC [9] are based the ring-ring (RR) scenario, while BNL team selected the linac-ring (LR) as a high luminosity version for eRHIC [10]. The LHeC team still pursues both RR and LR options [11,12].

Table 1 shows a sample of beam parameters and luminosities for these four colliders. For simplicity we had shown the case for electron-proton collisions. For the electron colliding with the heavy ions, the energy per nucleon is about 2.5 times lower than for the protons.

Each of four colliders has a number of proposed modes, energies and luminosity scenarios, which are impossible to fit into this review paper. I refer reader to a large number of papers in these proceedings and references therein: ENC at FAIR [16,17], ELIC/MEIC at TJNAF [18-20], eRHIC [21-27] and LHeC [28-33]

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#vl@bnl.gov

Table 1: Main parameters of Future Electron-hadron Colliders

Parameter (units)	**ENC**	**MEIC**[13]	**eRHIC**	**LHeC**	**LHeC**
Scheme	Ring-Ring	Ring-Ring	ERL-Ring	Ring-Ring	ERL-Ring
Circumference, km	0.575		3.8	27	27
Proton energy (GeV)	15	60	325	7,000	7,000
Electron energy (GeV)	3	3	20	70	60**
CM energy (GeV)	13.4	26.8	161	1,400	1,296
Collision frequency (MHz)	104	499	12	20	20
Number of protons per bunch/ # of bunches	0.36 10^{11} / 200	0.11 10^{11}	2 10^{11} /166	1.7 10^{11}/ 2808	1.7 10^{11}/ 2808
Number of electrons per bunch/ # of bunches	2.3 10^{11} /200	0.6 10^{11}	0.24 10^{11}/ NA	0.14 10^{11}/	0.02 10^{11}/
Proton beam current (A)	0.6	0.86	0.42	0.86	0.86
Electron beam current (A)	3.832	4.8	0.05	0.071	0.01
Norm. RMS proton emittance (μm rad, h/v)	2.3	0.8/0.8	0.2	3.73	3.73
Norm. RMS e-beam emittance ((μm rad, h/v)	820	75/75	23	1040/520	50
Polarization: protons/electrons (%)	>80/>80	>70/>70	70/80	NA/?	NA/90
RMS momentum spread: protons/electrons		/4.8 10^{-4}	3 10^{-4}/< 10^{-3}	/1.29 10^{-3}	
RMS bunch-length: protons/electrons (cm)	25/10	0.5/0.5	4.9/0.2	7.55/0.42	7.55/0.03
Protons, β* (cm, h/v)	10 [14]	2.5/0.5	5.0	230/60	10
Electrons, β* (cm, h/v)		2.5/0.5	5.0	12.7/7.1	12
Beam-beam tune shift per turn, protons (h/v)	0.014	/0.045*	0.015	0.0006/.0003	0.00007
Beam-beam tune shift per turn, electrons (h/v)	0.01	/0.24*	N/A	0.051/0.054	N/A
Laslett tune shift for protons	≥0.1	0.054	0.031		
Crossing angle (mrad)		22-100 [15]	10	1.4	0
Hourglass effect			0.851		0.91
Luminosity (x 10^{33} cm^{-2} sec^{-1})	**0.6**	**40**	**14.6**	**1.21**	**1.01**

** MEIC plan includes three IPs with beam-beam tune shift of 0.015 for protons and 0.08 for electron in each IP.*

***Only low-energy high-luminosity version is shown here*

ENC at FAIR

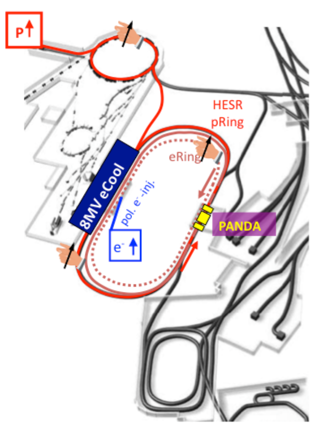


Figure 2: Layout of ERN at FAIR.

At idea emerged in 2008 to add 3.3 GeV polarized electron beam to HESR hadron ring with 15 GeV/c polarized protons and deuterons and to turn it into electron-nucleon collider (ENC). Collision would occur in PANDA detector, which would serve dual purpose for hadron and electron-hadron collisions. Polarized electrons would require a dedicated injector complex comprised of a polarized electron source, a linac and a full energy booster-synchrotron. Preliminary lattice for the ring and IR had been developed. This collider would require an 8-MeV, 3A e-cooler to reach its design parameters.

ELIC/MEIC at TJNAF [34]

In TJNAF (JLab) there is plan to built a polarized EHC ELIC and its low-energy stage MEIC. ELIC design goal to cover wide CM energy range between 10 GeV and 100 GeV having 3 colliders: Low energy: (3 -10 GeV) e x (3 – 12) GeV/c p (and ion); Medium energy (present focus) with up to 11 GeV e x 60 GeV p or 30 GeV/n ion; and High energy (future upgrade) with up to 10 GeV x 250 GeV p or 100 GeV/n ion (see Fig.3, gray color indicated high energy ELIC).

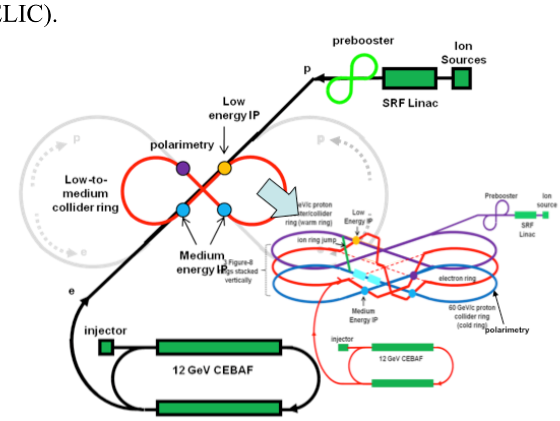


Figure 3. Proposed layout of ELIC. 3D layout of MEIC with 3 collision points (IPs) is shown in the right low corner.

ELIC/MEIC is the green-field design with a new polarized ion injection complex and six new "Figure-8" storage rings to ensure spin preservation and ease of spin manipulation. Luminosity concepts with 10^{33} up to 10^{35} cm^{-2} s^{-1} luminosity in multiple interaction points uses high bunch collision frequency (up to 1.5 GHz), very small bunch charge, very small beam spot size at collision points ($\beta^*_y \sim 5$ mm) and short ion bunches ($\sigma_z \sim 5$ mm). Keys to implementing these concepts are SRF ion linac, staged electron cooling and crab crossing.

Short-term design goals are focusing on completion of a MEIC conceptual design and scaling back vertical beta-star to 2 cm while preserving high luminosity. R&D issues optimizing ELIC design will be addressed iteratively.

Intermediate ELIC R&D goals are: Complete electron & ion ring designs (insert interaction region design, chromaticity correction w/ tracking); IR design & feasibilities of advanced schemes (develop a complete IR design, beam dynamics with crab crossing, travelling final focusing); Conceptual design of ion injector (bunch dynamics & space charge effect); Beam-beam interaction (multiple IPs with crab crossing and space charge).

eRHIC at BNL

At BNL we plan adding polarized 5-30 GeV electron beam to collide with variety of species in existing 2$B RHIC accelerator complex: from polarized protons with top energy of 325 GeV to heavy fully-striped ions with energy up to 130 GeV/u.

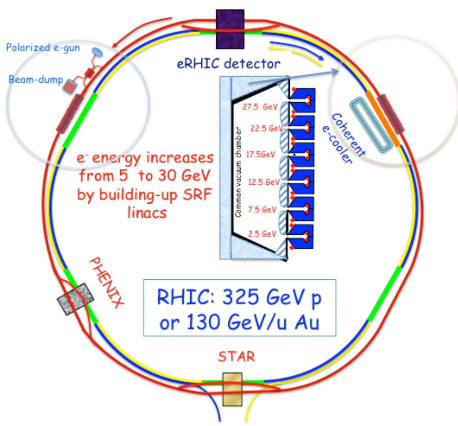


Figure 4: Layout of the ERL based, all-in-RHIC-tunnel, 30 GeV x 325 GeV high-energy high-luminosity eRHIC.

Since first paper on eRHIC paper in 2000, eRHIC design went through a number of iterations. Initially the main option eRHIC design was RR with LR been a back-up. In 2004 we published detailed "eRHIC 0th-Order Design Report" [5] including the RR cost estimate. After detailed studies we found that LR eRHIC has about 10-fold higher luminosity compared with the RR. Sine 2007 the LR, with its natural staging strategy and full transparency for polarized electrons, became the main option for eRHIC. In 2009 we completed technical design and dynamics studies for MeRHIC with 3-pass 4 GeV ERL. We learned a lot from the bottoms-up cost estimate for this $350M machine, and shelved the design.

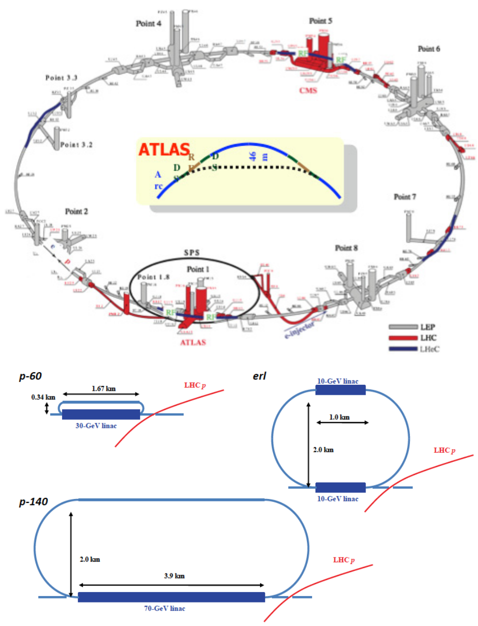
We returned to the cost-effective all-in-tunnel six-pass ERL for high-luminosity eRHIC design (see Fig.4). Electrons from the polarized pre-injector will be accelerated to the top energy by passing six times through two SRF linacs. After colliding with hadron beam in up-to three detectors, the e-beam will be decelerated by the same linacs and dumped. The six-pass magnetic system with small-gap magnets [23] will be installed from the day one. The staging of the electron energy from 5 GeV to 30 GeV will be done in steps by increasing lengths of the SRF linacs. eRHIC new IR design with 10 mrad crossing angle and with β*=5cm takes advantage of newly commissioned Nb3Sn quadrupoles [35]. Beam-beam effects in eRHIC and ways of suppressing kink instability are now well understood [26]. Integration of the detector into the IR is in advanced stage.

eRHIC's will use coherent electron cooling (CeC) [36] for the hadron beams. Being novel high-luminosity EHC, eRHIC has many technical challenges such as generating 50 mA of polarized electron current. R&D addressing these challenges is aggressively pursued by BNL and MIT. In collaboration with Jlab, BNL also plans experimental demonstration of CeC at RHIC.

LHeC at CERN

Similar to eRHIC, LHeC will require adding a lepton accelerator to the existing 7 TeV hadron proton and heavy ion complex at CERN. Discussions of adding leptons to the LHC started in 1990's and the first paper on LHeC was published in 1997 [37]. At present, two main options are considered for LHeC: a RR and a LR (see Fig.5). The linac-ring option has also two possible scenarios – a pulsed linac without energy recovery and an ERL.

(a)



(b)

Figure 5: Possible layout of the LHeC. (a) RR version with electron ring sharing LHC tunnel and 3 km of by-passes around detectors and RF; (b) three LR version: recalculating linacs (p-60 & p-140) and an ERL.

Adding 60 to 140 GeV electron beam to the LHeC has its unique complications, which are different from the most existing colliders and also from ENC, ELIC and eRHIC. Synchrotron radiation of such beams can consume significant part of its energy at one pass around the ring and operating such machine can be very power consuming. Present plug-power limit for LHeC is set at 100 MW level.

In the case of the lepton ring, the synchrotron radiation, which growth at the power four of the beam energy, is the limiting factor for the lepton beam current and, therefore, for the luminosity. This limits the ring-ring luminosity to 10^{33} level for 70 GeV electron energy. Similarly, an ERL will be limited in the e-beam current at high energies. In the case of a pulsed linac, the allowable electron beam current is inversely proportional to its energy. This dependence is less dramatic than that of ring-ring case, and this option may have higher luminosity at energies above 100 GeV.

The most attractive option for linac-ring case is an ERL, where most of the e-beam energy is recovered. But in contrast with eRHIC, in LHeC case turning electron beam around the LHC tunnel will generate as much power loss for synchrotron radiation as in the ring. Therefore, a traditional ERL option with recirculating arcs is attractive only at modest energies.

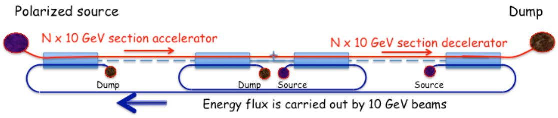


Figure 6: High luminosity LHeC with nearly-100% energy efficient ERL. The main high-energy electron beam propagates from left to right. In first linac it gains energy ~ 150 GeV (for N=15), collides with the hadron beam and the decelerated in the second.

In all cases presently under consideration, the electron beam intensity is well below the level allowed by the beam-beam tune shift of the hadron beam in the LHC. In other words, LHeC luminosity is not limited by the beam-beam effects and has a potential for an increase. Energy recovery linac without re-circulating arcs [38], shown in Fig.6, can be used to extend high luminosity LHeC operation to the electron energies above 100 GeV. Such ERL, which is more expensive version of LR, could push the LHeC luminosity to 10^{35} cm^{-2} sec^{-1} level with electron energy from 50 to 150 GeV.

CERN has a plan to develop LHeC conceptual design report by the end of 2010. At present time both RR and LR concept are pursued as potentially viable candidates for LHeC. Both RR and LR concepts have challenges. Being less traditional, the LR has to address additional challenges, the most non-trivial of which is generating polarize positrons.

CHALLENGES

Each of the future EHCs has significant challenges, some of which are summarized in Table 2.

There are some common threads such as using a novel untested crab-crossing for hadron beams. The other thread is the use of strong electron cooling of hadron beams to boost the luminosity. Challenges of operating a collider at low energy with space-charge dominated beams is a common thread for ENC and MEIC.

Table 2: Main Accelerator Physics Challenges for Future Electron-hadron Colliders

ENC	ELIC/MEIC	eRHIC	LHeC – ring/ring	LHeC - linac/ring
Limited space for electron ring	β*=0.5 cm 50x reduction	Polarized electron gun – 50x increase in current	Depolarization at the top energy	An adequate e+ source
Magnetized electron cooling Volt. 2x , Current 6x	HE Electron Cooling – 100x increase in the rate of cooling	Coherent e-Cooling (CeC) – New concept	Energy reach beyond 70 GeV for leptons	Potential 10x gain from cooling, but need special CeC
Large beam-beam tune shift in space charge dominated regimes	High current recirculating ring with ERL-injector New concept	Multi-pass SRF ERL 5x in current 30x energy	SR losses in the arcs	Potential 10x gain from multi-pass SRF ERL 30x energy
Crab crossing (compliance with PANDA)	Crab crossing 5x the angle for e^- New for hadrons	Crab crossing New for hadrons	Crab crossing New for hadrons	Crab crossing New for hadrons
Polarization life time in electron ring	Polarized ^{3}He production	Polarized ^{3}He production	3 km of by-passes	Totally new tunnel
Space charge limits beam dynamics, bunching (1→200)	New beam-beam parameter range 3-4x in ξ	Understanding of beam-beam affects New type of collider	Complexity of the sharing tunnel with LHC	Using crossing angle to avoid SR in IR
	Dispersive crab crossing Traveling focus New concepts	β*=5 cm 5x reduction	Need new injector	β*=10 cm 2.5x reduction
	Sub-nsec kicker with MHz rep-rate 50x shorter pulses	Multi-pass SRF ERL 3-4x in # of passes	Synchrotron radiation in the IR	Polarized e^- source
	Figure-8 ring spin dynamics New concept	Feedback for kink instability suppression New concept		

Systems beyond the state-of-the-art are shown in red. When possible the increase/reduction is shown.

CONCLUSIONS

Future electron-hadron colliders promise to deliver very rich physics not only in the quantity but also in the precision. They are aiming at very high luminosity two-to-four orders of magnitude beyond the luminosity demonstrated by the very successful HERA. While ENC and LHeC are on opposite side of the energy spectrum, eRHIC and ELIC are competing for becoming an electron-ion collider (EIC) in the U.S. Administrations of BNL and Jlab, in concert with US DoE office of Nuclear Physics, work on the strategy for down-selecting between eRHIC and ELIC.

The ENC, EIC and LHeC QCD physics programs to a large degree are complimentary to each other and to the LHC physics. In last decade, an Electron Ion Collider (EIC) collaboration held about 25 collaboration meetings to develop physics program for EIC with CM energy ~100 GeV [39]. One of these meetings was held at GSI, where ENC topic was in the center of discussions. First dedicated LHeC workshop was held in 2008 [40], with a number of dedicated workshops following it.

Intense accelerator R&D program is needed to address the challenges posed by the EIC.

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