NEXT GENERATION ELECTRON-ION COLLIDERS*

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Abstract

The next generation of electron-ion colliders promises very high luminosity, very high degree of polarization in both beams, multiple interaction points (IPs) and large range of energies. It will extend the reach and variety of attainable procresses in High Energy Physics and Nuclear Physics well beyond that provided by the first and only lepton-hadron collider, HERA. Some of these promises are based on new capabilities such as Energy Recovery Linacs (ERLs). We describe plans for these colliders which are under development by various laboratories, and the technology issues that are associated with these applications.

INTRODUCTION

Electron-ion (and positron-ion) collisions have unique properties that make them very valuable for high-energy and nuclear sciences. This was proven over 50 years ago by the seminal work on the form factor of nucleons by Robert Hofstadter which led to a Nobel Prize, and continued with ever increasing energy and luminosity to culminate in the lepton-proton HERA collider [1], providing an unprecedented energy reach, luminosity and lepton polarization. Not surprisingly new questions keep coming up and the need for accelerators with greater reach and greater variety of colliding species is ever present. In particular, the need to study QCD, improve the understanding of the structure and spin structure of hadronic matter, understanding the transition from the deconfined state of free quarks and gluons in the Big Bang to stable hadron matter can be addressed with higher precision in lepton-ion collisions. Hence, the new generation of electron-ion colliders is one of the key instruments to unravel the crucial fundamental physics questions.

Where does one go depends on the science one would like to pursue, and there is no single answer. The interest of nuclear and elementary particle physics span through a very large range of center-of-mass energies and energy ratios, variety of nuclear projectiles (from protons to uranium), use of electrons and positrons, very high luminosity and sometime very high degree of polarization.

In this work I will first outline what the accelerator physics issues are, and then describe three possible future machines which are quite different in approach and maturity of design: eRHIC, ELIC and LHeC.

ISSUES AND TECHNOLOGIES

The luminosity of an electron-ion collider can be written in terms of the fundamental machine limits, the beam-beam parameters and angular acceptance of the IP quads as

$$L = \left(\frac{4\pi\gamma_i\gamma_e}{r_i r_e}\right)(\xi_i\xi_e)(\sigma_i^{'}\sigma_e^{'})f$$

where round beams of the same size are assumed at the IP and subscripts ***i*** or ***e*** denote ions or electrons. The ξ are the respective beam-beam parameters, ***r*** are the classical radii and γ are the relativistic factors, and ***f*** the collision frequency. The angular rms spreads σ' at the IP are limited by the aperture of the final focus quadrupoles. Clearly the achievable luminosity scales with the assumed beam-beam parameter and a good understanding of this limit is necessary in any machine.

An ion beam-beam parameter limit of ξ_i=0.015 is supported by the performance of the RHIC, Tevatron and SPS proton colliders. HERA had limited operation to ξ_i ~0.003 to avoid increase of detector background due to beam loss caused by larger beam-beam parameter. The subject of the detector background requires further study. A very slow beam loss with lifetime of about 20 hours can be strongly affected by both the detector and collimation design as well as by electron cooling.

In approaching the design of a new accelerator one has to consider and resolve some of the issues outlined below.

Performance is mostly driven by the potential users of the proposed facility, and include: Richness of the selection of beam species, CM energy, variability of energy and energy-ratio (between the two colliding species), luminosity, polarization, bunch spacing, background, length of IP free of accelerator elements, number of IP's available, prospects of upgradeability and more. All of these affect the utility of the proposed facility to its users, and the users are usually the ones who have to make difficult choices.

Cost is in potential conflict with **performance**; New electron-ion colliders must use to a larger or lesser degree existing facilities in order to reduce the cost and/or improve performance. Of these, the ion machines and their injector-chains are the more expensive elements. Another variable of the cost vs. performance equation is **innovation**. One can use new technical solutions which, if used, can increase performance and/or reduce cost. However, using a new and untried approach may lead to **risk**. This has consequences - reviewers tend to be skeptical of new approaches and the contingency one has to carry influences the cost. Yet, progress requires some risks to be taken. Jawaharlal Nehru said wisely: "The policy of being too cautious is the greatest risk of all". In this paper I will try to portray the different path taken by

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future electron ion colliders and how innovation/risk dimensions are used to drive performance and cost.

The various issues and technologies of electron-ion colliders were discussed in various dedicated meetings and workshops [2, 3, 4]

Energy Recovery Linac

The idea of using an electron Energy Recovery Linac (ERL) to collide with other leptons is not new [5]. It was more recently proposed in the context of electron-ion colliders [6] and summarized by Merminga [7]. The advantages of the ERL for electron-ion colliders include a higher luminosity, given by the fact that the electron beam is used for the collision only in a single pass and thus withstands a much higher beam-beam parameter.

Round beams, naturally produced in ERLs, are optimal for maximizing the luminosity for a given beam-beam parameter, i.e. they provide for the use of round beams of equal size at the collision point(s). If the electron bunch intensity can always be adjusted to reach the ion beam-beam parameter ξ_i, the luminosity is only limited by the ion beam parameters:

$$L = \gamma_i f \; N_i \frac{\xi_i Z_i}{\beta_i^* r_i}$$

where N_i is the ion bunch intensity, Z_i is the ion charge, β_i^* is the ion beta function at the collision point. Thus, with the ERL, the luminosity can be improved for a given center-of-mass energy by reducing the energy of the electron beam while increasing the energy of the ions.

The ERL delivers a higher polarization than a self-polarizing ring since it can use modern super-lattice GaAs(Cs) photocathodes, which deliver electron spin-polarization between 80% to 90% with good quantum efficiency. In contrast with polarized storage rings imposing many restrictions on the ring geometry and beam energies, an ERL can be easily built with full polarization transparency for the electron beam at all energies. It is easily integrated with multiple electron-hadron interaction points (IPs) and detectors. It does not require spin rotators for longitudinal, radial or transverse polarizations. It has a large energy range at full luminosity and full polarization. Low emittance beams from the ERL make the IP optics simpler, in particular for providing very long "element free" straight sections for the detectors with greatly reduced synchrotron radiation background [8]. It can be upgraded in energy. Multiple-pass ERLs reduce the cost of the machine making it competitive with a storage ring. New single-mode SRF accelerator cavities provide the ERL with the ability to operate at the high currents which may be required in a collider [9]. ERLs are also capable to match the variation of ion bunch frequency at different ion energies.

The main risk in this approach is the availability of a polarized electron source with the necessary high current, an issue that should be resolved with well-focused R&D.

Electron cooling

A critical technology for electron-ion colliders is electron cooling for the ion beam. High-energy electron cooling is a new technology, and so far has been demonstrated only to a relativistic beam factor γ of about 8, while γ of 100 to 150 is necessary in some electron-ion colliders. In addition, cooling of colliding beams has not been done yet and no doubt there will be interesting consequences.

Cooling at the collision energy is needed when the intra-beam scattering (IBS) affects significantly the luminosity lifetime. Thus faster cooling is needed at lower energies or when the ion density is pushed higher to increase the luminosity.

Cooling a dense high energy ion beams is not easy, and requires high charge electron bunches (to make up for the high charge of the ions and overcome IBS) and low emittance (to provide a small angular spread of the electrons). This type of electron beam can be produced only by a linac. Electron cooling at these energies is under extensive investigation and prototyping at BNL [10].

Detector and IP considerations

The demand of a high luminosity ep/eA collider facility, *i.e.* for low β_i*, drives the installation of focusing machine elements close to the central detector. Interaction region design with machine elements as close as ±1m to the interaction region would significantly limit the achievable detector acceptance. The IP area is of concern to both accelerator physicists and detector physicists. Machine parameters such as bunch separation, crossing angle, location of accelerator elements near the IP, bunch length, synchrotron radiation fan generated by beam separation, beam loss and more affect the detector design and performance. These are critical and challenging requirements. [8].

The eRHIC design provides a machine-element free region of ±3m, and a machine-element free region of approximately ±5 m is possible [11]. ELIC provides ±2m.

In the design of LHeC, a magnet-free space of at least 2.4m was specified in the interaction region to provide sufficient space and acceptance for the experimental detector. [12]

Crossing angle [13] helps with the beam-beam interaction of parasitic collisions and reduces synchrotron radiation problems, but requires fitting high voltage crab cavities into the collider. For eRHIC, the required transverse voltage was calculated in Ref. [8]. Assuming a design similar to the KEKB crab cavity [15] at ωRF ~2π·200MHz, and β-functions of β^* = 1m and β_{crab} =400m, the transverse voltage for a 250GeV proton beam and 5mrad crab angle is about $V_\perp$ ~15 MV. This is not practical at RHIC. Another important issue for the crab crossing is the very high tolerance imposed on the amplitude and phase stability of the crab cavities [14] by the hadron beams. In the case of ELIC it is estimated that a sub-ppm amplitude stability will be necessary, [16] a very challenging goal.

ELIC

ELIC [17] is a very high luminosity collider designed to provide longitudinally and transversally polarized light ions - p, d, ^{3}He and Li, and unpolarized light to medium ion species. The extremely high design luminosity in this medium energy collider is based on a long list of innovative (but untested) ideas. The use of CEBAF as the injector to a 3-7 GeV, 1-3 A electron ring will provide cost saving. By adding a positron source to CEBAF injector, a positron beam can also be accelerated in CEBAF and accumulated and polarized in same storage ring. An ion accelerator complex will be added, including a 150 GeV, 1 A collider ring with 4 interaction regions. A novel feature is the figure-8 shape of the booster rings, electron collider ring, and the ion collider ring. Although it increases the cost by requiring more bending magnets, such a configuration ameliorates the issue of spin maintenance at acceleration and allows one to arrange desired spin orientation for all light-ion species at all energies.

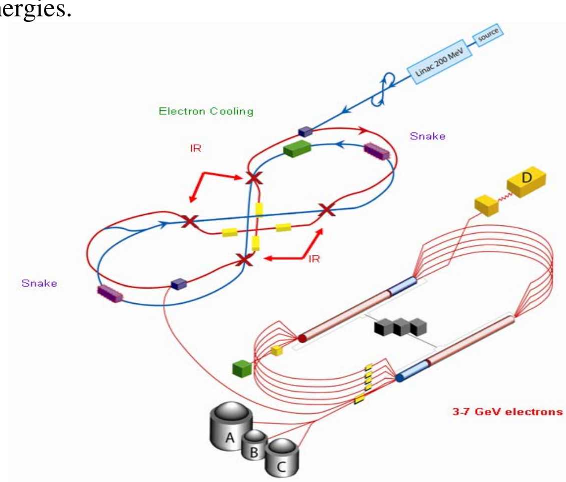

Figure 1: Layout of ELIC.

Another critical component of the ion complex is a 75 MeV ERL-based electron cooler. The high luminosity of ELIC relies on a low emittance and very short (5 mm or less), ion bunches [18,19], which is to be provided by aggressive electron cooling. In order to provide the extremely high current and low emittance for ELIC, the use of a circulator-cooler ring is proposed as a way to accumulate the necessary electron current from a 75 MeV ERL. The very short ion bunches are required for an extremely strong beam focusing at the collision points and crab-crossing of the colliding beams in ELIC. In addition, the luminosity requires an extremely high bunch repetition rate (up to CEBAF's RF frequency of 1.5 GHz).

The short ion bunches provide also for a large synchrotron tune (exceeding the beam-beam tune shift in ELIC case), which presumably eliminates the synchro-betatron non-linear resonances in the beam-beam interaction. Another novel feature of ELIC is the use of flat beams (by lowering the x-y coupling at fixed beam area), which is predicted to reduce the ratio between IBS and electron cooling.

The four IPs of ELIC will have equidistant fractional phase advance, with the expectation of effectively reducing the critical beam-beam tune shift to a value normalized to one IP.

A special spin rotation scheme has been developed to transform the electron spin from vertical in arcs to longitudinal in IPs in a wide energy range, with polarization insensitive to the energy. Self-polarization in arcs supports the injected polarization of electron beam and provides polarization of positron beam.

Table 1: Basic parameters for ELIC.

Parameter	Unit	Value	Value	Value
Beam Energy	GeV	150/7	100/5	30/3
Circumference	km	1.5		
Crossing straights	m	346 x 2		
Bunch collision rate	GHz	1.5		
# of particles/bunch	10^{10}	.4/1.0	.4/1.1	.12/1.7
Beam current	A	1/2.4	1/2.7	.3/4.1
Energy spread, rms	10^{-4}	3		
Bunch length, rms	mm	5		
Beta-star	mm	5		
IP focal parameter	m	6		
Space for detector	m	5		
Extended beam size*	mm	6		
Crab crossing angle	rad	.1	.1	.1
Crab field integral	Tm	.24	.16	.048
Horiz. emit. norm.	μm	1/100	.7/70	.2/43
Vertical emit., norm.	μm	.04/4	.06/6	.2/43
Beam-beam tune shift (vertical) per IP		.01/ .086	.01/ .073	.01/ .007
P sp. charge tune shift		.015	.03	.06
Lumi. per. IP*, 10^{34}	$cm^{-2}s^{-1}$	7.7	5.6	.8
Luminosity lifetime	h	24	24	>24

*) Beam horizontal size in IP focusing triplet

Overcoming space charge at injection is another challenge at ELIC. Stripping injection can be used to stack polarized proton and deuteron beams in the pre-booster after 200 to 400 MeV linac. To minimize the space charge impact on the transverse emittance, a circular painting technique is suggested for stacking. Such a technique was originally proposed for stacking a proton beam in the SNS [20].

The reduction of the 4D emittance growth at stacking 1-3 Amps of light ions is of a critical importance for the effective use of electron cooling in the collider ring, since the initial electron cooling time is determined by the 6D emittance value of the injected ion beam.

eRHIC

RHIC is a high-luminosity ion-ion and polarized protons collider [21]. eRHIC adds an electron accelerator to collide with the RHIC ions [6,22].

eRHIC's preferred design uses a superconducting electron ERL for reasons outlined above, but a more conventional ring-ring version is also under study. R&D on electron cooling, ERL physics, polarized sources, beam-beam studies, head-tail type instability of the proton beam (kink instability), electron beam transverse disruption by the beam-beam interactions, proton beam emittance growth due to fluctuations of electron beam current, electron beam size, and transverse collision offset, cost estimates and other relevant subjects are being carried out by the institutes collaborating on eRHIC.

eRHIC will provide 3-20 GeV polarized electrons and polarized positrons 50-250 GeV polarized protons; 100 GeV/n gold ions and 167 GeV/n polarized 3He ions. The luminosities will be over 10^{33} $cm^{-2}s^{-1}$ for e-p collisions and over 10^{31} $cm^{-2}s^{-1}$ for e-Au collisions. The expected polarization is at least 70% for proton beams and over 80% for electron beams.

The Center-of-Mass Energy (CME) range covered by eRHIC is from 30 to 140 GeV.

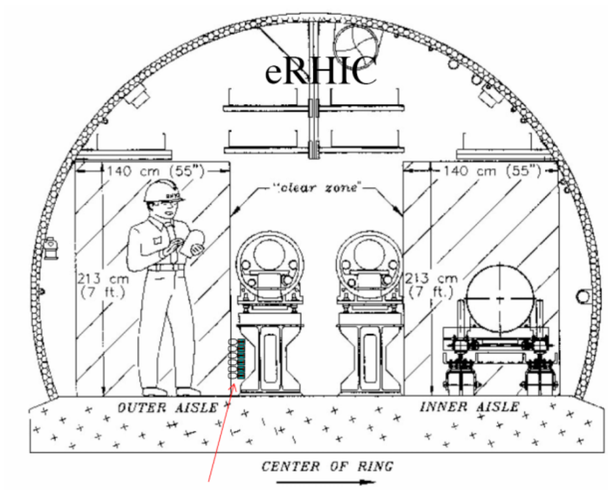

Figure 2: eRHIC's multiple passes in the RHIC tunnel.

The electron beam by-passes the STAR and PHENIX experimental halls. Initial acceleration to the energy of 0.5 GeV is done by the smaller pre-acceleration linac. A 4 GeV ERL is used in a five pass acceleration / deceleration scheme. The two high-energy re-circulating passes of the ERL are sharing the RHIC tunnel with the ion rings, leading to a significant cost saving (see Figure 2). The electron ERL sections are located inside the RHIC tunnel in four of the six available straight sections.

To provide a positron beam, the last ERL turn is closed upon itself to form a storage ring for the positrons. Polarized positrons will be generated through polarized gammas similar to techniques that are being developed for the ILC, cooled in a small cooling ring and accelerated to the desired energy by the linac and stored for collisions. Naturally the luminosity of the positrons will be lower due to the use of a storage ring.

The design parameter tables 2,3 are based on setting the limiting value of the ion beam-beam parameter to ξ_i=0.015, which seems to be realistically achievable, based on the experience of the RHIC operation with polarized proton beams and assuming a dedicated single collision point.

Positrons will collide with the ions while circulating in the storage ring. Because of this the luminosity of positron-ion collisions will be one order of magnitude lower than for electron-ion collisions.

The ERL is based on a 703.75MHz SRF cavity designed for ERL service [23]. The design assumes 20 MeV energy gain per cavity. 200 cavities are used in a 600m long linac (consisting of four 150m long sections that fit in the RHIC straight sections) to provide 4 GeV acceleration in one beam pass. The average luminosity is expected to be about 1/3 of the peak luminosity, leading to a luminosity integral of 530 (580) inverse picobarn per week for the protons (gold) hadrons at the higher energy.

Table 2. eRHIC Parameters for e-p collisions.

	High energy		Low energy	
	p	e	p	e
Energy, GeV	250	20	50	3
Num. of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Particles/bunch, 10^{11}	2	1.2	2.0	1.2
Beam current, mA	420	260	420	260
95% norm. emit, μm	6	115	6	115
Rms emittance, nm,	3.8	0.5	19	3.3
β^*, cm	26	200	26	150
Beam-beam parameter	0.015	2.3	0.015	2.3
Rms bunch length, cm	20	0.7	20	1.8
Polarization, %	70	80	70	80
Pk Lumin. 10^{33} $cm^{-2}s^{-1}$	2.6		0.53	

Table 3. eRHIC Parameters for e-Au collisions.

	High energy		Low energy	
	Au	e	Au	e
Energy, GeV/n - GeV	100	20	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	1.1	1.2	1.1	1.2
Beam current, mA	180	260	180	260
95% normal. emit, μm	2.4	115	2.4	115
Rms emittance, nm,	3.7	0.5	7.5	3.3
β^*, cm	26	200	26	60
Beam-beam parameter	0.015	1.0	0.015	1.0
Rms bunch length, cm	20	0.7	20	1.8
Polarization, %	0	0	0	0
Pk Lumin. 10^{33} $cm^{-2}s^{-1}$	2.9		1.5	

LHeC

The LHC provides a unique opportunity to probe matter with precision at the shortest length scale, as short as 0.0001 fm with high luminosity. The idea of constructing an electron accelerator at some future time to collide leptons with LHC protons or ion beam (thus making LHeC) has been described in Ref. [12]. This proposed upgrade of LHC to include the possibility of an LHeC is based on rather robust assumptions, fitting a machine not to dissimilar from the LEP design back into the LHC tunnel. The proton beam parameters are taken as the LHC design values. Certainly the expensive piece of hardware is the LHC, although the electron machine at this scale is not cheap. The tentative location of the ep interaction region is shown in Figure 3.

The electron current (and thus bunch charge) is dictated by an assumption on a reasonable power to be available at the CERN site, and is certainly a very sensitive function of the electron beam energy. The current is related to the power and energy through:

$$I_e = 0.351 mA \cdot \left(P_{RF} / MW\right) \cdot \left(100 GeV / E_e\right)^4$$

With electron energy of 70GeV, 50MW of RF power and SRF cavities, the total beam current is 71 mA.

The luminosity of LHeC is high with conservative beam-beam parameters. That comes as no surprise given its extremely high energies of both projectiles, as can be seen from the expression for the luminosity in terms of the beam-beam parameters.

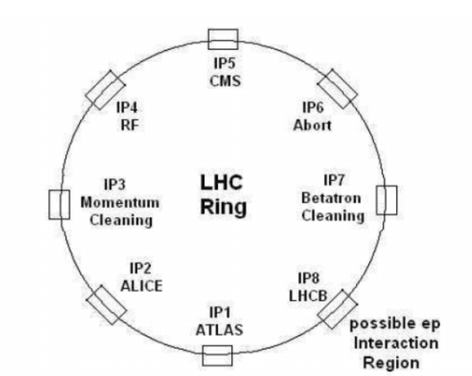

Figure 3. Layout of LHeC.

Table 4. LHeC Parameters for e-p collisions.

Property	Unit	Leptons	Protons
Beam energies	GeV	70	7000
Total beam current	mA	74	544
Particles/bunch	10^{10}	1.04	17.0
Horizontal emittance	nm	7.6	0.501
Vertical emittance	nm	3.8	0.501
Horizontal β^* at IP	cm	12.7	180
Vertical β^* at IP	cm	7.1	50
Energy loss per turn	GeV	0.707	$6 \cdot 10^{-6}$
Radiated energy	MW	50	0.003
Bunch frequency / spacing	MHz / ns	40 / 25	
Center of mass energy	GeV	1400	
Luminosity	$10^{33} cm^{-2} s^{-1}$	1.1	

SUMMARY

Proposed future electron ion colliders span a wide range of parameters and approaches to risk – innovation – performance – cost trade-offs. What is common to all is the high luminosity. eRHIC is intermediate in CM energy. It is based on an operating ion machine with polarized protons and high luminosity. eRHIC is intermediate in innovation, with the electron ERL as its main innovation, and its main challenge is to demonstrate its polarized electron source.

LHeC has the highest CM energy by far being based on the LHC and LEP. The main shortcoming of LHeC is the absence of proton polarization, and uncertainty with regard to electron polarization. The LHeC design is very conservative and its main challenges are time and budget.

ELIC is limited by its site to lighter ions. In contrast with eRHIC and LHeC, ELIC faces the burden of adding the most expensive part of a lepton-ion collider – the chain of ion machines and has a limited range of ion, but it promises the highest luminosity. In terms of innovation (and attendant risk) ELIC is by far the most innovative design.

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REFERENCES

[1] F. Willeke, these proceedings , APAC07, Indore, India.
[2] I. Ben-Zvi and G. H. Hoffstaetter, Summary M5 W.G. on Lepton-Hadron Colliders, Snowmass 2001
[3] http://www.jlab.org/intralab/calendar/archive04/eic/
[4] https://www.bnl.gov/qcdfp/
[5] M. Tigner, Nuovo Cimento 37, 1228-1231 (1965).
[6] I. Ben-Zvi, et al, NIM A463, 94 (2001).
[7] L. Merminga, these proceed., APAC07, Indore, India.
[8] C. Montag et al, Proc. PAC05 and also http://www.bnl.gov/cad/eRhic/Meetings/eRHIC_Talks/RHIC_Plan_Meet/CM_RPM.pdf
[9] E. Pozdeyev, in [4].
[10] I. Ben-Zvi, Proc. EPAC06.
[11] V. Litvinenko et al,, Proc PAC05
[12] J.B. Dainton et al, DESY 06-006, Cockcroft-06-05
[13] R. B. Palmer, SLAC-PUB-4707 (1988)
[14] K. Oide, K. Yokoya, Phys. Rev. A 40, 315, (1989)
[15] K. Hosoyama et al, Proc. SRF05 Cornell University
[16] C. Montag, private communication
[17] Ya. Derbenev et al, Proc. RuPAC 06
[18] Ya. Derbenev et al., ICFA Newsletter, No 30, (2003)
[19] Ya. Derbenev et al., Proc. EPAC04
[20] J.Holmes, et al., Proc PAC05
[21] T. Roser, these proceedings , APAC07, Indore, India.
[22] http://www.sc.doe.gov/Scientific_User_Facilities/History/20-Year-Outlook-screen.pdf
[22] R. Calaga et al, Proceedings, EPAC'04