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FROM HERA TO FUTURE ELECTRON-ION COLLIDERS*

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Abstract

An overview of the proposals of new electron-ion colliders - e-RHIC at BNL, EIC at JLab and LHeC at CERN - in the light of experience with HERA is presented.

INTRODUCTION

The year 2007 is the last year of the operation of lepton-proton collider HERA at DESY. This unique machine opened for the scientific exploration the area of physics, which had not been easily accessible with any other colliders or fixed target experiments. During 15 years of the HERA operation the remarkable results have been obtained, including the precise data on 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]. As HERA leaves the scientific exploration scene, several future projects are under consideration in the USA and Europe. Those projects intend not only to extend the knowledge of physics area studied at HERA, but also to provide the new exploration tools by involving lepton collisions with heavy ions as well as with polarized protons and polarized light ions. All of the future lepton-ion colliders projects are based on the extension of already existing machines. The JLab considers the addition of. ion and electron storage rings to the upgraded CEBAF electron accelerator in order to form the ELIC collider [2]. BNL seeks to extend capabilities of the existing RHIC machine by the addition of an electron accelerator, thus creating the eRHIC machine [3,4]. Correspondingly the LHeC collider has been proposed as a possible future extension of the LHC at CERN [5]. The future lepton-ion colliders aim to considerably larger luminosity of lepton-proton collisions than used at HERA. Also new colliders will operate in different from HERA the center-of-mass energy (CME) regions. The eRHIC and ELIC machines consider their operation at the CME area of 20 to 100 GeV, with the luminosities ranging in 10^{32}-10^{34} $cm^{-2}s^{-1}$ values. The LHeC goal will be to explore the collisions at 1.4 TeV CME with the luminosities about 10^{33} $cm^{-2}s^{-1}$.

Table 1 presents the summary of main beam parameters for electron-proton collisions for the collider designs discussed in this paper as well as for HERA. For eRHIC and ELIC the parameters are shown for the electron-proton operation mode at the highest design energy.

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PHYSICS OBJECTIVES

For a long time the lepton-hadron scattering has been a very important tool of scientific discovery. The scattering, presented a clean way to look inside the structures bound together by strong forces and study the components of those structures. Before and during HERA era several fixed target experiments have explored the process of Deep Inelastic Scattering of leptons on nucleons in order to gain the knowledge on the nucleon internal structure, including the structure of the nucleon spin, and to improve understanding of QCD theory of strong interactions. After HERA collider had been built, considerably higher CME gave physicists the opportunity to investigate structure functions of protons at considerably better spatial resolution and in the range of small x values (fractional moment carried by a nucleon constituent). Besides higher CME, another advantage of a collider against a fixed target experiment is better separation of products of a scattering process, which allows for the complete examination of the final states.

The future lepton-ion colliders aim to continue exploration of quark-gluon structure of nucleons, extending kinematic range and adding new dimensions of that exploration [6]. Collisions of polarized leptons with polarized proton or light ion beam at eRHIC and ELIC will contribute into the investigation of the proton and neutron spin content, which still remains a puzzle. The examination of the final states will allow to do the measurements of the structure functions marked by quark flavors.

The lepton collisions with heavy ions will provide a new tool for studies of partonic picture of nuclei and nuclear binding. The gluon saturation state, the Color Glass Condensate, can be created and studied in lepton-heavy ion collisions in eRHIC and ELIC, as well as in low-x lepton-proton collisions in LHeC.

All studies mentioned above should not only provide the knowledge of specific structures and states of the matter but also would improve considerably our understanding of the QCD theory. Some specific precision QCD theory tests are also planned as a part of the lepton-ion collider physic program.

Looking for new physics beyond the Standard Model the LHeC physics program includes the search and study of leptoquark particles [5].

COMMON DESIGN ISSUES

Some issues of the collider design are similar for all future lepton-ion colliders. The experience from HERA design and operation is used for various design aspects.

Table 1: Main parameters for HERA and future lepton-ion colliders. eRHIC and ELIC parameters are given for electron-proton collisions at highest design energy.

	HERA		eRHIC ring-ring		eRHIC ERL-based		ELIC		LHeC	
	p	e	p	e	p	e	p	e	p	e
Energy, GeV	920	27.5	250	10	250	10	225	9	7000	70
Bunch frequency, MHz	10.4		14.1		14.1		1500		40	
Bunch intensity, 10^{11}	0.72	0.29	1	2.3	2	1.2	0.04	0.075	1.7	0.14
Beam current, A	0.1	0.04	0.21	0.48	0.42	0.26	1	1.8	0.54	0.07
Rms emittance,x/y, nm	5.1/5.1	20/3.4	9.5/9.5	53/9.5	3.8	1.0	5.1/0.2	5.1/0.2	0.5/0.5	7.6/3.8
β^*, x/y, cm	245/18	63/26	108/27	19/27	26	100	0.5/0.5	0.5/0.5	180/50	13/7
Beam size at IP, x/y, μm	112/30		100/50		32/32		5/1		31/16	
Max beam-beam parameter per IP	0.0012	0.037	0.015	0.08	0.015	2.3	0.0064	0.086	0.0008	0.05
Bunch length, cm	19	1	20	1.2	20	1	0.5	0.5	7.6	0.7
Polarization, %	0	45	70	80	70	>80	>70	80	0	0
Distance of first quad from the IP, m	2		1		3		3		1.2	
Crossing Angle, mrad	0		0		0		30		2	
Peak Luminosity, 10^{33} $cm^{-2}s^{-1}$	0.04		0.47		2.6		75		1.1	

Interaction Region Design

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 superconducting magnets.

Careful treatment of synchrotron radiation in the IR includes application of the collimation, absorbers and the protection masks at the appropriate locations. The HERA operation experience calls for a careful design of vacuum environment in the detector region, including pipe conditioning, adequate pumping and avoiding excessive heating by HOM [7]. Following HERA lessons, the tight electron orbit control and the beam-based alignment have to be considered in the IR design in order to minimize synchrotron radiation problems.

Because of the proximity of the ion and electron beam trajectories, magnets of a special design are applied in the interaction regions. The septum half quadrupole, invented for HERA [8], found its application for the eRHIC and LHeC interaction regions. The ELIC IR design includes a Lambertson type quadrupole [2].

All collider designs employ the fast beam separation to avoid the parasitic beam-beam collisions. ELIC and LHeC collision geometry includes the crossing angle (Table 1) which not only serves the purpose of fast separation but also simplifies the accommodation of synchrotron radiation fan. To prevent the luminosity loss due to the crossing angle the crab crossing has to be used which presents important R&D item for those colliders. In the case of ELIC 24 MV integrated voltage kick is required for the crab crossing. The design of crab cavities has to be developed which satisfies challenging requirements of high current operation, including tight tolerances on phase and amplitude stability. Possible harmful beam dynamics effects originating from the coupling of longitudinal and transverse motion has to be evaluated. The crossing angle is not used in the eRHIC design [9]. The fast beam separation is initiated at the collision point by the dipole field integrated into the detector magnet.

Beam-beam Limitations

The harmful effect of the beam-beam interactions on the beam dynamics is one of most fundamental factors limiting the collider luminosity. The beam-beam interactions in the lepton-ion colliders may have special features because of the very different colliding particles. The importance of precise matching of the beam cross sections of the colliding beam had been established at the HERA operation [11] and became the design requirement for all future collider designs. On the other side all designs, except LHeC, aim to achieve considerably higher beam-beam parameters (ξ) than reached in HERA (Table 1). The HERA proton ξ was limited to quite small value because of the detector background issues. One can hope to overcome this limitation by improved collimator and detector design. The large eRHIC proton ξ=0.015 is based on the experience of the RHIC operation with proton-proton collisions [12].

The electron beam-beam restrictions in HERA came from the proximity of the synchro-betatron resonances, which limit the available tune space, and from the coherent beam-beam motion, which causes the considerable increase of the proton beam emittance [1]. The eRHIC ring-ring design assumes high electron

ξ=0.08, following the B-factories achievements. The beam-beam simulations verified that at the eRHIC ring-ring design parameters the threshold for the emittance blowup due to the coherent motion is not exceeded [13]. Further simulations, including synchrotron motion, should be done to confirm the feasibility of the high electron ξ.

In the ELIC design, with electron ξ=0.086, large synchrotron tune is assumed which should improve the beam-beam limit by eliminating synchro-betatron nonlinear resonances. Also, the equidistant phase advance between collision points should help minimize total beam-beam parameter [2]. The beam-beam simulations are planned to confirm this design approach.

In the ERL-based eRHIC design the electron beam is used for collisions only on one pass and the allowed strength of the beam-beam force acting on the electron beam can be considerably increased. The beam-beam limitation factors in this design are quite different from the ring-ring designs. The simulations have been done to study the electron beam disruption, the kink instability and to establish tolerances on fluctuations of electron beam parameters [14].

In eRHIC and LHeC a mode of concurrent operation with the lepton-ion and ion-ion collisions at different collision points is possible. That raises a question about possible beam-beam compensation and achievable value of the total ion ξ in such collision setup.

Frequency Matching

The eRHIC and ELIC should be able to operate at a similar range of ion energies. Since the variation of the ion velocity considerably affects the ion revolution frequency, special provisions have to be made to match lepton and ion bunch frequencies at different ion energies.

To operate in the proton energy range from 50 to 250 GeV the eRHIC ring-ring design includes 20cm adjustment of the electron ring circumference. Present solution is based on moving the whole arcs and lengthening two long straight sections ("trombone"). Preservation of tight misalignment tolerances, demanded for the beam polarization preservation, would be additional requirement during this circumference adjustment.

The ELIC design takes an advantage of very high ion RF harmonic number. The ion bunch frequency can be kept constant for all ion energies using adjustment of RF harmonic number. The horizontal orbit displacement in the arcs does not exceed 12mm.

The bunch frequency matching is not considered to be an issue for the ERL-based design. The range of RF frequency tunability of superconducting accelerating structure ($\Delta f/f \sim 10^{-3}$) is wide enough to provide necessary adjustment of the electron bunch frequency.

ERHIC

The eRHIC design is developed by the collaboration led by accelerator physicists at BNL and MIT-Bates [3]. eRHIC takes an advantage of having the existing RHIC ion machine, which presently operates with heavy ion (Au) or polarized proton collisions. The range of ion species provided by RHIC for eRHIC will include polarized protons (50-250 GeV), polarized ^{3}He ions (up to 167 GeV/n) and gold ions (up to 100 GeV/n). Two design options of eRHIC have been developed concurrently.

ERL-based eRHIC

In this design the electron beam is accelerated to the collision energy of 10 GeV in a superconducting energy recovery linac (ERL) [15]. This design option opens way to luminosities above 10^{33} cm^{-2}s^{-1} and accommodates developing accelerator technologies. The design (see Figure 1) includes a high intensity electron gun (polarized for e-p or unpolarized for e-Au experiments), the 0.5 GeV pre-accelerator ERL, the main 2 GeV ERL and five recirculating passes (four of them are placed in the RHIC tunnel aside of the existing two ion accelerator rings). The nominal design energy of electron beam ranges from 3 to 10 GeV with a possibility of upgrade to higher energies (up to 20 GeV). Multiple collision points are possible.

The ERL-based design approach brings a number of advantages. Considerably relaxed beam-beam tolerance for the electron beam allows for higher ion beam intensity and/or smaller beam emittances and, therefore, opens way to higher luminosity. The tolerance for smaller ion beam emittances allows to get maximum benefits from the electron cooling system which should be installed on RHIC as part of the RHIC-II upgrade.

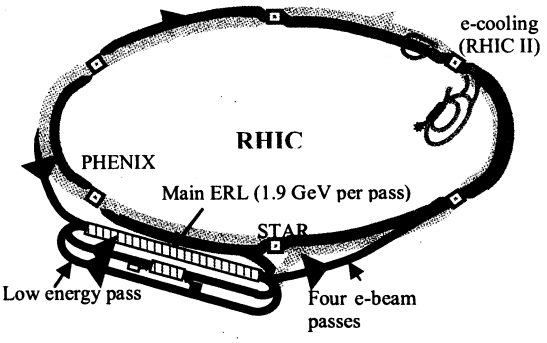

Figure 1. ERL-based design option of eRHIC uses the energy recovery linac as the electron accelerator.

For polarized electron beam there is no need in spin rotators, the longitudinal polarization at the collision point can be achieved by proper slight readjustment of energy gains in pre-accelerator and main ERLs.

The small emittance of the electron beam produced by the linac simplifies the design of the interaction region. The luminosity benefits from round beam collisions geometry and the interaction region quadrupoles can be

moved as far as 3m from the collision point, making easier the IR integration of a large acceptance detector.

The key R&D item is the development of the ERL technology for high power beam. This development goes inline with the superconducting RF technology developments for the e-cooling project at RHIC [16]. The state-of-art design of basic element of the ERL, superconducting 703.75 MHz 5-cell RF cavity, was developed in BNL [17]. The design allows minimization and efficient damping of the HOM, opening a way for higher electron currents. Test energy recover facility, which includes beam recirculation, will verify the technology at high beam current.

For the operation with polarized electron beam, very high intensity polarized electron source needs to be developed, which presents major R&D item. R&D program is planned for the design development of a large cathode gun with existing current densities (50 mA/cm^2), which is considered as a way to higher polarized electron intensities.

For heavy ions (Au) the electron cooling will be used at the top storage energy (100 GeV) to counteract the IBS and maximize the collider luminosity. Proton beam will be pre-cooled at the injection energy to lowest emittance allowed by the beam-beam limit.

The design of multiple recirculating passes in the long RHIC tunnel is a crucial factor for the minimization of the project cost. Variants under consideration include the use of small gap (<1cm) magnets [18] and the application of a FFAG type pass which can accommodate all recirculation orbits [19].

To include the positron beam into the design, the compact storage ring could be added, for the positron beam accumulation and storage.

Ring-ring eRHIC

In another eRHIC design the polarized electron (or positron) beam of 5-10 GeV energy is stored in a storage ring (Figure 2) [20]. This option is technologically more mature and achieves the peak luminosity at 4.10^{32} cm^{-2}s^{-1} level. Because of similarity of the beam energy and intensity, the accelerator technology applied and developed in B-factories can be used at the storage ring design. The full energy injector can be either cold or warm conducting linac, or '8-figure' booster synchrotron..

The size of the ring (1/3 of RHIC circumference) is short enough to provide self-polarization of initially unpolarized positron beam on the time scale of 20min. The equilibrium polarization of electrons or positrons may reach 80% at reasonable beam orbit tolerances [21]. Although some of the lepton energies can not be used because of spin depolarizing resonances. Solenoidal spin rotators will be used to provide longitudinal polarization at the interaction point.

Special features of the storage ring design include the application of superbend magnets [22], the variable transverse emittance and variable ring circumference. The superbend magnets, triplet bending magnets with varying bending radius of inner magnet, help to reduce the luminosity drop at lower energies (to $1/\gamma$ dependence). The application of superbends also provides reasonably short positron self-polarization time down to 5 GeV. The superbends together with lattice adjustments should allow to vary the transverse emittance of leptons to match the ion beam size at different energies.

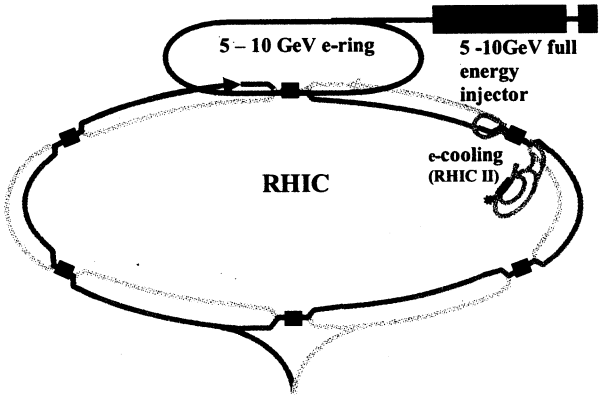

Figure 2. The layout of the ring-ring design option of eRHIC.

To maximize the luminosity the IR quadrupoles are placed as close as 1m from the collision point which presents considerable challenge for the high acceptance detector design. The special attention should be taken about experimental solenoid compensation to prevent the enhancement of depolarization effects.

ELIC

The design efforts for this electron-ion collider are led by the Jefferson Lab [2]. The range of ion species includes polarized protons (30-225 GeV), polarized D and ^{3}He ions, and ions up to A=208 (up to 100 GeV/n). The lepton side includes polarized electrons or positrons from 3 to 9 GeV. The existing CEBAF accelerator, after planned 12 GeV upgrade, would serve as the injector accelerator for the leptons (Figure 3). Besides that two 'figure-8' storage rings should be built, for lepton and for ion beams. Four intersections between the rings provide locations for four possible experiments. The lepton storage ring also would serve as the pre-accelerator for the ions.

In the quest for very high luminosity, the ELIC design uses quite a different approach than that of eRHIC. While the bunch intensities are not so high, the design employs very high bunch repetition rate, small transverse and longitudinal emittances and very strong focusing.

Since small emittances are needed, the electron cooling of high energy protons presents a crucial design issue and major R&D item. The present design suggests the usage of a circulator cooler ring with continuous re-injection (and extraction) of individual electron bunches from (and to) an energy recovery linac. It is proposed also to use

flat ion beams in order to reduce the ratio of IBS to cooling rates.

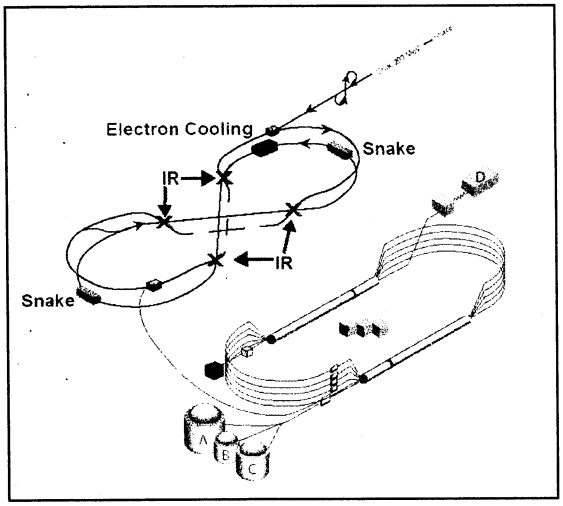

Figure 3. ELIC is based on two figure-8 rings to store electron and ion beams.

The figure-8 shape of the storage rings was selected to eliminate spin sensitivity to energy for all species. The set of longitudinal axis Siberian Snakes as well as controlled vertical orbit distortion are used to provide required proton spin orientation at the collision points. In lepton ring the set of solenoids and spin rotators performs tasks of maintaining longitudinal spin orientation at the interaction points, keeping spin tune at the one half value and maintaining proper vertical orientation of the spin in the arcs. This complex polarization control scheme in the lepton ring requires careful evaluation of spin matching condition in order to minimize introduced depolarizing effects. For positrons, which are injected unpolarized, the self-polarization time without additional wigglers would be 2 h at 7 GeV energy.

The detector design benefits from having +-3m magnet-free space around IPs. On the other side very high bunch repetition rate provides a considerable challenge for detector data acquisition and triggering. R&D is planned which will define the acceptable repetition rate for the ELIC detector.

LHeC

Recently a possible design of lepton-proton collider at CERN has been under consideration [5]. In this design the lepton storage ring is added in the tunnel above the existing LHC magnets. The lepton beam injector system is identical to that used at LEP. Preliminary luminosity evaluation, the lepton ring lattice and the interaction region design for such collider have been made. The IP8 can be used for the lepton-proton collisions after the physics program of the LHCB experiment is completed.

Proposed LHeC electron beam energy of 70 GeV is much higher than that in eRHIC and ELIC. Because of the high energy the major limiting luminosity factor for this collider will be the available RF power required to replenish the beam energy losses due to the synchrotron radiation. Assuming superconducting RF cavities (1GHz) and 50 MW allowed RF power, the maximum electron beam current will be limited to about 70mA for 70GeV electron beam.

The lepton ring lattice based on the FODO cell structure provides an optimal emittance from the point of view the interaction region design and beam-beam limitations.

The electron beam superconducting IR triplet is placed at 1.2m from the collision point, which seems acceptable for LHeC detector acceptance for largest part of the physics program.

CONCLUSIONS

Several designs of the lepton-ion colliders are under development, including eRHIC at BNL, ELIC at JLab and LHeC at CERN. The collider designers are using the experience obtained during years of HERA operation. In the same time new ideas and technologies are applied in the accelerator designs which should allow to achieve considerably higher luminosities. At the end the cost and the importance of the physics that can be explored at a particular collider will be important factors for a success of one or another design.

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