Status of polarized lepton-ion colliders

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Abstract. Lepton-Ion colliders may provide a decisive tool to explore so far unresolved problems in fundamental research, in particular those concerning the QCD-structure of the nucleon. Collaborations in the United States (ELIC and eRHIC) and in Europe (ENC@FAIR and LHeC) pursue different collider designs. In most cases, both colliding species will be spin polarized. Concentrating on the accelerator physics issues this paper gives an overview of specific design features and challenges.

1. Introduction
At HERA, transverse electron or positron polarization was achieved by self-polarization due to the Sokolov-Ternov effect. Spin rotators allowed for longitudinally polarized $e^{\pm}$-beams which were interacting with protons at center of mass energies $>$ 300 GeV. Proton beam polarization was not achievable at HERA. A polarized internal gas-target experiment (HERMES) was utilized for 'double-polarized' lepton-ion experiments instead. Since the shutdown of HERA, such experiments have to resort to fixed external targets, for instance at COMPASS or at JLAB. Such experiments are limited in CM-energy (see fig. 1). A further disadvantage is frequently created by the dilution of target polarization and/or the restricted acceptance of the detection system which are both due to the necessities of solid target technology.

In order to improve the situation, several new collider concepts have been proposed. The main goal is to provide collider operation, as in HERA, but to obtain polarized ion beams in addition. Of course, the highest possible luminosity has to be achieved. An economic approach towards such a first 'double-polarized' collider is to make use of existing facilities. In the US, the availability of $>$ 200 GeV polarized proton beams at BNL invites to attach a suitable polarized lepton machine. This is known as the eRHIC project [1]. The CEBAF 12 GeV-polarized electron beam is the basis for a project termed ELIC. For ELIC, an ion-ring and the lepton storage ring must be added. This investment would be rewarded by high flexibility and by optimized performance [2]. In Europe, two suitable ion machines exist or are under construction: The LHC at CERN and HESR at GSI/FAIR which form the starting point for the LHeC [3] and the ENC@FAIR [4] project respectively. ENC@FAIR is limited in CM energy ($\sqrt{s} = 14 GeV$), on the other hand it is probably the project which requires the smallest additional investment. As it was the case in HERA, LHeC would not offer double-polarized experiments, but, of course, unprecedented center of mass energy. For the US based projects staged approaches are being discussed; these are dubbed MeRHIC (BNL) and MEIC (JLAB).

Presently, careful consideration of the physics-potential against the required investment into the accelerator infrastructure is needed. It is the purpose of this article to discuss the features and challenges of the different projects with respect to accelerator physics issues.
2. General considerations

Under simplifying assumptions - equal horizontal and vertical emittances, round beams - the collider luminosity is given by

\[ L = \frac{f_{\text{coll}} N_{I,e}}{4\pi \beta^* \epsilon} \]

with \( f_{\text{coll}} \) = bunch collision frequency, \( N_{I,e} \) = respective ion and electron number per bunch, \( \epsilon \) = geometric beam emittance in equilibrium, \( \beta^* \) = beta-function at interaction point (IP). In general, it is difficult to optimize \( L \) by tweaking a single parameter because of the strong interdependence with the other variables. One important reason for a limitation of \( L \) lies in the existence of accelerator instabilities which do not allow sustained operation of the storage rings at the desired luminosity. This can be visualized as any mechanism which introduces a 'tune shift' or 'tune-spread', hence driving the particle motion into a resonance.

A prominent example is 'chromaticity' which leads to a tune spread due to the energy distribution of the stored particles. The chromaticity-contribution of, e.g., the quadrupole focusing towards the IP is \( \propto \beta_{\text{quad}} k_{\text{quad}} \) (\( k_{\text{quad}}, \beta_{\text{quad}} \) = focusing strength and beta-function of/at quadrupole). This restricts the lowering of \( \beta^* \), since \( \beta_{\text{quad}} \propto \frac{1}{\beta^*} \).

Space charge is another example, here the non-linear Coulomb forces of the bunch charge distribution cause the tune spreads. These 'intra-beam' effects become less pronounced at higher energies. A similar - and sometimes more severe - restriction results from the beam-beam interaction at the IP which also causes non-linear focusing effects and consequently tune spreads. These 'beam-beam tune shifts' \( \xi_{I,e} \) are reciprocal with regard to the particle species and inversely proportional to \( \gamma = \frac{E}{m} \) (\( E, m \) total energy and mass of particle, respectively):

\[ \xi_I \propto \frac{N_I}{\gamma_I}; \quad \xi_e \propto \frac{N_e}{\gamma_e} \]
A main difference between the four projects is that two of them (eRHIC and LHeC) rely on 'Linac-Ring' concepts, the other two make use of HERA-style ring/ring collisions.

The so-called 'Linac Ring-' (LR-) concept has much less strict requirements towards electron orbit stability since each of the leptons only has to pass the interaction region once (or at most a few times). Much larger values for $\xi_e$ are then tolerable. Therefore, a LR-concept gives more room to maximize $N_I$ (in turn allowing to reduce $N_e$) which is especially interesting for high energy ion-machines where the 'Intra-beam' space charge is less severe. The LR concept allows for much lower electron current (small $\xi_I$), which also significantly reduces the synchrotron radiation losses (for given Energy, $N_e$ and $f_{coll}$). LHeC ($\gamma_p \approx 7000$ - index p stands for proton as ion species) and eRHIC ($\gamma_p \approx 300$) are presently pursuing the LR-configuration. However, besides this conceptual advantages, the LR-concept requires additional R&D. These issues are discussed in section 2.1.

In the 'Ring-Ring' (RR-) option both limitations suggested by eq. 2 have to be fulfilled. The two RR-projects require electron storage rings with high electron bunch charges - similar to existing $e^+/e^- -$storage rings such as KEK-B. In RR-schemes the polarized electrons are comparatively easy to generate, either by self polarization or by using a polarized electron source. A further requirement is to achieve a sufficient spin lifetime and/or equilibrium lepton polarization - see sec. 3.2. The two concepts pursuing a RR-option are ELIC ($\gamma_p \approx 60 - 250$) and ENC@FAIR ($\gamma_p \approx 15$). For a given circumference of the ring, $N_e$ is limited by 'single-bunch' instabilities. Under this restriction it is still possible to increase $L$ by maximizing $f_{coll}$. However, economic (and thermal) problems due to synchrotron radiation also set a limit to $f_{coll}$.

For the ion storage rings (relevant for all projects) the outcome of optimization depends on the availability of beam cooling - see the dependence of eq. 1 on the equilibrium emittance $\epsilon$. Here, new techniques may provide significant improvement over the present state of the art - some of these are discussed in section 3.1.

2.1. Accelerator R&D issues in the LR-case

Currents of $30 \leq I_e < 100 \text{ mA}$ are presently discussed for MeRHIC and eRHIC LR-schemes, the beam energy ranges between 6 and 30 GeV. The instantaneous beam power of the electron beam at the IP is then in the several 100 MW range which is unpractical to sustain in c.w. mode. Instead of using recirculation as in a storage ring, the LR scheme recuperates the energy of the particles after they have passed the IP. Such an 'energy recovery linac' (ERL) was demonstrated with great success at JLAB a few years ago. This ERL operates at $\approx 150 MeV, 10 mA$ unpolarized beam and decelerates the electrons back to a few MeV. A research group at BNL [5] addresses the adaptation of an ERL for the MeRHIC/eRHIC project, especially designing suitable superconducting r.f.- accelerating structures and handling the beam dynamics at the higher energy gain and beam loading.

In the LR-approach, the high intensity spin-polarized electron beams have to be generated by polarized electron sources. Such sources are based on photoemission from NEA-photocathodes made from III/V-semiconductor compounds [6]. NEA photosources can fulfill all requirements of an EIC concerning beam quality, time structure and intensity. The main problem of the NEA-photosource is that the cathode suffers from instability due to interaction of the NEA surface with beam induced particles, especially ions. This jeopardizes the continuous long-term operation required at an LR-based EIC. Presently, the average beam currents used at c.w. machines such as MAMI or CEBAF [7, 8] are of the order 0.2 mA which is about two orders of magnitude lower than required. On the other hand, the current density of the existing sources is almost the same as required ($\approx 100 mA/cm^2$). It is argued that, since cathode damage should be proportional to the current density, a sufficient operational stability can be expected. This expectation, however, awaits unambiguous experimental verification. Such an experiment is not simple, since progressing towards higher beam currents creates new problems like thermal...
load and transmission losses due to increased emittance. MIT and BNL have started studies in which they promote a very large aperture gun (MIT) [9] or to use a multitude of cathodes in time sharing mode (BNL). The latter system, the so-called 'Gatling gun', uses a r.f. deflector system which directs beams from the different cathodes towards a common trajectory [5].

3. Beam equilibria

3.1. Ion beam cooling

The emittance $\epsilon$ in equilibrium results from the balance of beam heating and cooling effects. To achieve a satisfying luminosity (eq. 1), the introduction of an efficient cooling mechanism is vital for most of the projects. For the electrons, synchrotron radiation provides such a mechanism whereas ion beams require other means, such as electron- or stochastic cooling. Stochastic cooling does not work efficiently at the high particle densities needed at an EIC. In electron cooling, the ion beam is superimposed by an electron beam of the same velocity (i.e. $\gamma_{e,\text{cool}} = \gamma_I$). The 'cooling time' is the time constant of the equilibration process. In the widely applied 'Parkhomchuk model' [10] this time scales with a high power of $\gamma_I$. Therefore reasonably small cooling times for relativistic ions require very long interaction volumes in very homogeneous longitudinal fields ('magnetized cooling' with $\Delta B/B \approx 10^{-5}$) in addition to extremely high electron beam currents. Classical electron cooling uses d.c. electrostatic acceleration with beam-energy recuperation. This approach seems feasible at ENC@FAIR, where $\gamma_I = 15$ calls for a 8 MV electrostatic accelerator. Cooling times of about 20 minutes can be achieved by using the already foreseen HESR-cooler-solenoid with an interaction length $l_{\text{cool}} = 24$ m and $I_{\text{cool}} \approx 3$ A [11]. The voltage and current would exceed those of the FERMILAB-cooler - which parades the highest voltage of all existing coolers - by a factor of two and six respectively.

Application of d.c. electron cooling to ion beams of significantly higher energy does not seem to be promising. As an alternative, Derbenev [12] suggested to use an ERL based storage ring for ELIC ('r.f.-cooler'). The very high peak current ($\approx 30$ A) bunches can be swept over the ion bunches. The system is proposed to operate at $\gamma_I \leq 250$. Another new concept is 'coherent-cooling', which is related to the stochastical cooling principle [13] but uses a superimposed electron beam as 'pick up' and undulator induced instabilities to amplify the signals 'imprinted' in the electron beam. The amplified modulations are then fed back to the ion beam in another electron/ion interaction stage. This advanced method could provide substantial cooling also for the highest ion beam energies. BNL presently sets up a proof of principle experiment to make a first demonstration on a highly charged heavy ion beam within the next years.

3.2. Spin equilibria

The successful acceleration and storage of polarized protons in RHIC [14] established beam polarization in the range of several hundred GeV. Except for LHeC, where so far no ion polarization is foreseen, similar techniques will have to be applied for the other projects. Whereas ENC@FAIR relies on a combination of a solenoid with a partial helical snake [15], ELIC intends to use a figure of eight (FO8) storage ring for both particle species: The FO8-ring has a constant zero spin tune and therefore does (in first order) not suffer from imperfection resonances. This may lead to a considerably simpler scheme for spin stabilization. It is therefore expected that better flexibility and lower polarization losses can be achieved. In the case of the electrons (RR-schemes only) synchrotron radiation may drive the leptons into depolarizing resonances also in storage ring operation, hence creating additional complications. Snake stabilization of an overall horizontal polarization is not very effective in this case: the Derbenev-Kondratenko-Mane formula [16] yields a $\gamma^{-5}$ dependence of spin lifetime - presently restricting this scenario to energies $\leq 3$ GeV [17, 18]. Another option - relying on the experiences made at HERA for almost 30 GeV - is to achieve longitudinal polarization at the IP by spin rotators before and after the IP and to have the polarization parallel to the 'spin-stable' vertical direction in the
recirculating arcs. Using self-polarization in this case also gives a handle on achieving polarized positron operation in an EIC. In the LR-design $e^-$ depolarization is not critical since the sojourn time of the electrons is many orders of magnitude smaller than in a storage ring.

4. Layout of different EIC-configurations

4.1. ENC

ENC@FAIR plans to utilize the HESR ion storage ring presently under construction at GSI/FAIR (see fig. 2). HESR allows to store protons with a total energy of nearly 15 GeV. A counter-circulating polarized electron beam with 3.3 GeV will provide $\sqrt{s} = 14$ GeV. As electron preaccelerator a booster synchrotron or a pulsed linac can be foreseen. The HESR tunnel can also incorporate the electron ring. HESR is intended to be operated in a first round of experiments with antiprotons, using the PANDA detector. After this period PANDA can be employed for $e^-/p$-collisions at a luminosity of $2 \cdot 10^{32} s^{-1} cm^{-2}$. More aggressive scenarios - using for instance a crossing angle for beam separation for which the luminosity reduction can be avoided by introducing 'crab-crossing' - allows for values of $L \approx 6 \cdot 10^{32}$ without leaving the present state of the art of accelerator physics \cite{11}. Compliance of such a scheme with the needs of the experiments is presently under investigation.

4.2. MeRHIC/e-RHIC

The MeRHIC 'staged' approach foresees to install a 4 GeV ERL in a loop attached to RHIC. The final 'eRHIC' will feature an ERL with 4.9 GeV energy gain (2 LINACS with 2.45 GeV each) per round trip which is installed inside the RHIC tunnel. Fig. 3 shows the stacking of electron beams in a common vacuum chamber during the six turn acceleration process towards 30 GeV. After reaching the highest energies the beam is decelerated on the same orbits and leaves the...
system towards the 0.6 GeV pre-accelerator, where it is further decelerated to a few MeV. IP’s are foreseen at the already existing detector stations PHENIX and STAR. A dedicated detector at a third IP may be added at a later stage.

![Figure 3. eRHIC: ERL with 6 turns in RHIC tunnel offering multiple collision points [1].](image)

Coherent cooling (sec. 3.1) may allow to reduce ion beam emittance, resulting in estimated values for luminosity of the order $10^{34} \text{cm}^{-2}\text{s}^{-1}$ for $40\text{GeV} < \sqrt{s} < 180\text{GeV}$ (see fig. 1).

4.3. MEIC/ELIC
The MEIC/ELIC scheme uses the CEBAF accelerator as injector. Electron and ion rings would be build as figure of 8 (FO8-) systems, offering optimized conditions for spin stabilization. Furthermore, a FO8-system certainly yields a better starting point for providing longitudinally polarized Deuterons, a feature that is extremely difficult to achieve in conventional systems due to the low gyromagnetic anomaly of the Deuteron. A medium energy solution (MEIC) operates with 600 m circumference electron and ion rings, with up to 60 GeV (protons, superconducting bending magnets) colliding on $e^{-}$ with 5-11 GeV. In the final stage (ELIC) an extension of the rings to 1800 m circumference would allow for 250 GeV ions colliding with 10 GeV electrons. In fig. 4 a sketch of the FO8 three ring stacked geometry is presented. The upper ion ring is for 12 GeV (normal conducting magnets). Up to 4 different IP’s are possible to be individually optimized for luminosity or detector acceptance. This design allows for advanced focusing concepts which could allow to reach luminosities of almost $10^{35} \text{cm}^{-2}\text{s}^{-1}$ (fig. 1).

4.4. LHeC
For LHeC a RR-concept could also be envisaged, however, the necessary installations in the LHC tunnel seem to be difficult to coordinate with LHC-operation. Furthermore, the problems of achieving a sufficient spin lifetime and equilibrium electron polarization at energies $\approx 60\text{GeV}$ are presently not solved. One of several options for a LR based LHeC [19] makes use of a 60 GeV
electron accelerator (three pass at 2*10 GeV gain, either pulsed, see fig. 5, or alternatively c.w., as ERL). Since $\sqrt{s} \approx 1300$ GeV is by far the largest CM-energy, a completely different range of physics topics can be addressed. However, this requires also a formidable detector, similar in complexity to those installed at LHC[3].

$10^{33} \text{cm}^{-2}\text{s}^{-1}\int L = 100 \text{ fb}^{-1}, E_{\gamma} = 60\text{GeV}$

**Figure 4.** MEIC figure of 8 storage rings with normal conducting booster [2].

**Figure 5.** LHeC operational scheme with LR configuration [3].
ENC at FAIR | ELIC at JLAB | eRHIC at BNL | LHeC at CERN
---|---|---|---
Space charge limits | $\beta^* = 0.5 \text{ cm}$ | Polarized electron gun | Depol. at the top energy |
Beam dynamics | $50^\text{th}\text{ reduction}$ | $50^\text{th}\text{ increase}$ | Polarized lepton source |
Bunching $1 \rightarrow 200$ | | | |
Limited space for electron ring | HE El. Cooling | Coherent Electron Cooling | E $> 60$ GeV |
| $1000^\text{th}\text{ increase}$ | New Concept | for Leptons | |
8MV magnetized electrostatic 3A cooler | High current | Multi Pass SRF ERL | Multi pass SRF ERL |
| recircul. ring with ERL-injector | $5^\text{th}\text{ increase in current}$ | $5^\text{th}\text{ increase in energy}$ | $5^\text{th}\text{ increase in current}$ |
| New concept | $30^\text{th}\text{ increase in energy}$ | $30^\text{th}\text{ increase in energy}$ | $3-4^\text{th}\text{ in } \#\text{ of passes}$ |
Crab cross. | 50° in angle for e- | New for hadrons | New for hadrons |
New for hadrons | Crab cross. | 5° in angle for e- |
| New concept | New for hadrons | |

| | Never explored beam beam param. range 3-4 in $\xi$ | Understanding of beam beam effects New type of collider |
| | Dispers. crab cross. Travelling focus new concept | $\beta^* = 5 \text{ cm}$ |
| | $5^\text{th}\text{ reduction}$ | |
| | Sub-ns kicker 50°shorter pulses | Multipass SRF ERL 3-4° in $\#\text{ of passes}$ |
| | Figure of 8 ring dynamics | Feedback for kink instability suppress. |
| | New concept | New concept |

Table 1. Challenging aspects of different EIC-schemes as extracted from [1]. Text in red indicates increases/reductions beyond state of the art.

5. Summary
Several proposals to build electron ion colliders exist which span a wide range in center of mass energies and luminosities. There is an obvious correlation between these parameter ranges and the investment costs. At the present stage all projects head forward to provide conceptual design reports and also towards cost estimates. All projects could start to operate in the first half of the next decade (2020+X). A summary of the R&D issues and challenges is given in table 1.

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