ACHIEVING HIGH LUMINOSITY IN AN ELECTRON-ION COLLIDER*

Yaroslav Derbenev, Geoffrey Krafft, Byung Yunn and Yuhong Zhang#,
Thomas Jefferson National Accelerator Facility, Newport News, VA 23693, U.S.A.

Abstract

A future electron-ion collider is required to deliver a high luminosity exceeding 10^{33} cm^{-2}s^{-1} per detector for probing the hadronic structure of matter. At JLab, a medium energy ring-ring collider (MEIC), based on the CEBAF SRF linac as a full-energy electron injector and a green-field design of an ion complex, is one of several proposals to meet this science need. The present MEIC design relies on high bunch repetition and high average-current colliding electron and ion beams with short bunch length and small transverse emittance for reaching the high luminosity goal. This is an approach significantly different from traditional hadron colliders. In this paper, we present a review of this luminosity concept and its impact on the accelerator design, particularly design of the ion complex for delivering required ion beams. We will also discuss some new ideas towards the realization of this high collider luminosity concept.

INTRODUCTION

As articulated in the latest Long Range Plan [1] issued by US DOE-NSF Nuclear Science Advisory (NSAC) Committee, a new electron-ion collider (EIC) is critically needed as a gluon microscope for the emerging QCD frontier. While the EIC science programs are under active development, a set of basic machine requirements has been gradually converging. Among them is a minimum luminosity of 10^{33} cm^{-2}s^{-1}, roughly 100 times higher than the final achieved luminosity of HERA, the world's only and highly successful high energy electron-proton collider at DESY recently decommissioned.

JLab has been engaged in feasibility studies and conceptual design of a polarized electron-ion collider for over a decade. The present baseline is a medium energy ring-ring collider (MEIC) with a CM energy up to 52 GeV [2] while a future energy upgrade (ELIC) will extend the CM energy to or beyond 100 GeV [3]. Since the very beginning, the focus of the JLab EIC studies has centered on achieving ultra-high luminosity over multiple (3 or 4) collision points, an order of 20 to 100 times higher than the desired luminosity requested by the Long Range Plan. Such unprecedented high luminosity is achievable in principle due to MEIC or ELIC employing a special luminosity concept which has already been proved in several lepton-lepton colliders but is still new to colliders involving hadron beams. JLab possesses a unique opportunity to adopt this luminosity concept for its MEIC design due to the following two facts: the 12 GeV upgraded CEBAF SRF linac will serve as a full energy injector into the MEIC electron ring; and being a green field, the MEIC ion complex can be specially designed to produce ion beams with optimized time and spatial bunch structures. Therefore, MEIC and its energy upgraded version ELIC hold a very attractive promise of an ultra-high luminosity in a range from a few 10^{34} to above 10^{35} cm^{-2}s^{-1}, depending on acceptance of the detectors and arrangement of interaction regions.

Though the JLab EIC designs and their luminosity concept were proposed nearly a decade ago and reported in various conference proceedings [3,4] and a design report [5], we will present a comprehensive review in the next section with emphasis on the luminosity concept itself rather than machine design details. In the third section we will discuss ideas and accelerator design for forming the required ion beams to support high luminosity.

MEIC LUMINOSITY CONCEPT

Briefly, the key to the MEIC high luminosity concept is that both colliding electron and ion beams have short bunch lengths and small transverse emittance such that a strong final focusing can be adopted to reduce beam spot sizes to a few μm at collision points, hence, combined with a high bunch repetition rate and high averaged current, greatly boosting the collider luminosities. To illustrate this concept, let us first examine how ultra high luminosities had been achieved in several lepton-lepton colliders.

Lessons Learned from Lepton-Lepton Colliders

The present world records of the highest achieved luminosity are held by e+e- colliders at the KEK-B and PEPII B-factories, with sustained peak values of 2.11 and 1.21 times 10^{34} cm^{-2}s^{-1} respectively [6,7]. These high luminosities can be attributed to the following machine design features and key beam parameters (see Table 1): (1) high bunch repetitions, up to 508.6 MHz for KEK-B and 476 MHz for PEPII; (2) high average beam current, up to 3 A; (3) short bunches, with RMS bunch lengths shorter than 1 cm; (4) small transverse emittance, of the order of a few mm-mrad (normalized) on vertical direction and very high aspect ratio; (5) extremely small (less than one cm) vertical beta-star (betatron function at collision points). It is clear that (1) and (2) lead to modest bunch charges, about several 10^{10} electrons or positrons per bunch, hence lesser effects of single bunch instabilities. (5) is possible since (3) ensures the hour-glass effect is still relatively small even under a very strong final focusing (beta-star), combined with (4), leading to micrometer beam spot sizes at collisions points. In addition, (4) reduces the beam spot size inside the final focusing quads, and thus requires smaller apertures in

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# yzhang@jlab.org

magnets and makes the interaction region optics design much easier.

Table 1: Main Parameters for e+e- Colliders and MEIC

		KEK-B (e-/e+)	PEPII (e-/e+)	MEIC (p/e-)
Current	A	1.6/1.2	1.9/2.9	1/3
Bunch repetition	MHz	508.6	476	750
Particles/bunch	10^{10}	1.6/1.2		0.4/2.5
Bunch length σ_z	mm		11/10	7.5/7.5
Horiz. emit., norm.	μm-rad		52/35	0.35/54
Vert. emit., norm.	μm-rad		1.1/1.3	0.07
β^*_x	cm	120 / 120	48/44	4/4
β^*_y	cm	0.59 / 0.59	1/0.8	0.8/0.8
Beam-beam par. vert.		0.13/0.13	0.05/0.06	0.007/0.03
Luminosity (10^{34})	$s^{-1}cm^{-2}$	2.11	1.21	1.4

Luminosity Concept

The luminosity of a collider with head-on collisions is given by [8]

$$L = \frac{1}{4\pi} f_c \frac{N_e N_p}{\sigma_x^* \sigma_y^*} \quad (1)$$

assuming both colliding bunches are short and their spot sizes are matched. The key luminosity parameters are bunch collision frequency (f_c), number of particles per bunch (N_e, N_p) and spot sizes at the collision point (σ_x*, σ_y*). Their values depend on the collider design and are usually limited by collective beam effects. Among these limiting effects, the most important is the beam-beam effect characterized by the following parameter

$$\xi_{y,p} = \frac{r_p N_e}{\gamma_p} \frac{\beta^*_{y,p}}{2\pi\sigma_y^*(\sigma_x^* + \sigma_y^*)} \quad (2)$$

where r_p is the classical radius of proton and γ_p is the relativistic factor of the proton. Thus the luminosity formula (1) can be rewritten as

$$L = \frac{\gamma_p N_p f_c \xi_{y,p}}{2 r_p \beta^*_{y,p}} \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \quad (3)$$

and a similar formula using the electron beam-beam parameter. It is clear that a high current $N_p f_c$ is preferable for a higher luminosity; however, the bunch charge is nevertheless limited not only by the beam-beam parameters of the other beam but also by additional collective beam effects such as ion space charge tune-shifts. Presently there is no good theory which can predict maximum allowable values of the beam-beam parameters of a collider; however experiences from years of operation of existing colliders indicate that a value of 0.035 is a practical limit of the total beam-beam parameters for hadron beams and roughly a factor of 4 larger for lepton beams thanks to their synchrotron radiation damping [9]. With the above facts, the luminosity can be optimized by pushing up bunch collision frequency within limits of the beam currents and squeezing values of beta-star.

For ring-ring colliders involving hadron beams, there are traditionally very small numbers of bunches per beam, ranging from just a handful (9 for SPS) to several dozen (36 for Tevatron) [9]; therefore their collision frequencies are very small. With relatively large bunch charges (up to 10^{11}) in order to maintain even a modest beam current, bunch lengths are usually very long (of the order of 0.5 to 1 m) partially due to limits of collective effects and also slow processes of accumulating and acceleration of particles. Long bunches prevent a strong final focusing (small beta-star) due to the hour-glass effect, and combined with large transverse emittance if no beam cooling is applied, lead to large beam spot sizes at collision points, as a result, pulling down luminosities.

The luminosity concept proved at the B-factories spearheads with very large bunch collision frequency by storing tens to hundreds times more bunches in the rings, and hundreds times smaller beta-stars (the spot sizes at collision points) through strong final focusing enabled by short bunch lengths. Though bunch charges should be also scaled down proportionally to maintain small charge densities and thus similar severity of collective beam effects, the high average currents can be achieved by a very large number of bunches. The net effect, combined with appropriate interaction region design discussed below, is several order of magnitude increase of luminosity

Design of MEIC Colliding Beams

It has been a primary design strategy of MEIC to break away from the traditional approach of hadron colliders and to adopt the new luminosity concept of short-bunch and high-collision-frequency for the first time in a ring-ring collider involving ion beams. At JLab, the CEBAF recirculated SRF linac delivers an extremely good quality CW beam at 1497 MHz bunch repetition rate, split three ways to three experimental halls of fixed targets. After completion of the current 12 GeV energy upgrade, there will be no further upgrade requirement to utilize this facility as a full energy injector to the electron storage ring of MEIC. Stacking and storing an electron beam with up to 3 A average current is technically proved in B-factories. It should take very short (less than a second) time to fill the MEIC electron ring by the CEBAF linac, thus if there is a science need, CEBAF can be operated simultaneously for both the MEIC collider and the fixed target programs. A technical challenge of providing high RF power to compensate energy loss due to synchrotron radiation of the high current beam leads us to keep the bunch repetition rate below 1 GHz at least initially; hence a choice of 750 MHz had been made for the present conservative baseline design [10].

On the ion beam side, we need to produce and store high average current beams with matched properties in terms of bunch repetition rates, length and emittance. The key beam parameters for a typical MEIC point design are summarized in Table 1, in order to implement the new luminosity concept. Such ion beams do not exist yet, however, they are technical feasible given advances of accelerator technologies over the last several decades, notably in ion sources, SRF linacs and the cooling of ion beams. It should be noticed from Table 1 that number of protons per bunch in MEIC is only 4×10^9, a factor of 10 to

50 times smaller than that in a traditional ion collider. Significant studies have been devoted over the last several years at JLab to the conceptual design of such a modern ion complex. A brief description of this ion complex plus a process of formation of MEIC ion beams will be presented in the next section. What we want to point out here is, being a lepton lab, we have in our hand a green-field design of an ion complex. This provides us a great opportunity to create a new facility for producing ion beams with desired time and spatial structures without being constrained by decades-old out-dated legacy systems or suffering a tremendously high cost for updating and even rebuilding almost every part of an existing facility.

A comment should be made on the aspect ratios of transverse emittance of MEIC colliding beams. Like the cases of two B-factories, the stored electron beam of MEIC tends to become highly flat due to synchrotron radiation. This large aspect ratio of transverse emittance (and transverse beam sizes) could be preserved with a ring optics of zero or very small residual x-y coupling, and therefore could be exploited for enhancing luminosity and optimizing interaction region design. The ion beams of MEIC, on the other hand, naturally have a round shape since the energies are too low to emit synchrotron radiation. However, they can also be made oval or highly even flat if electron cooling is applied such that the aspect ratios of transverse emittance are determined by a balance of (non-isotropic) intra-beam scatterings and (isotropic) electron cooling [11]. Studies indicated that emittance aspect ratios of cooled ion beams depend on ion energy and ring optics in addition to the electron cooler design. They could approach 5 to 7 for a 60 GeV proton beam in the MEIC baseline design but can be as high as 25 for 250 GeV protons in the ELIC case.

ERL-Ring Collider vs. Ring-Ring Collider

A linac-ring collider was considered at an early stage of the EIC Studies at JLab. In that proposal, an ion beams stored in a ring collides with an electron beam from the CEBAF SRF linac. The key advantage of a linac-ring collider is that a much larger beam-beam disruption can be tolerated by the electron beam since it is not stored for a long time in a ring. A large beam-beam parameter could increase luminosity in principle as shown in Eq. (3). Nevertheless a major upgrade of CEBAF to an energy recovery linac (ERL) is required in order to avoid drawing hundreds of GW RF power from the linac (and wall plug). This ERL-ring approach has also been adopted recently at BNL as the baseline of the eRHIC design [12] as well as at CERN as one option of the LHeC design [13]. While this is an attractive concept, our studies show that its luminosity advantage over a ring-ring collider is not significant when the bunch repetition rate is very high as in the MEIC design [14]. Further, an electron beam with a modest to high average current must be made available to reach a high luminosity. This current requirement is very difficult to meet for the MEIC case since the electron beam must be highly polarized. A clever idea of employing a circulator electron ring had been suggested, in which an electron beam recirculates several hundred rounds while colliding with an ion beam before being ejected and sent to the CEBAF SRF linac for energy recovery. Therefore it can effectively reduce the required beam current from the CEBAF linac from 2 to 3 A to 20 to 30 mA, a factor of hundred reduction. However even the reduced current is still a hundred times beyond the current state-of-the-art of the polarized electron sources; thus a tremendous R&D effort is needed to close such a giant gap. A high demand of electron source R&D combined with an ERL upgrade of CEBAF, but with only a small luminosity gain compared to the alternate ring-ring collider led us to choose naturally a ring-ring collider as the MEIC baseline and rely on the new concept described above for achieving a high luminosity.

Interaction Regions

The luminosity concept discussed in the previous subsections could not work without a proper design of the interaction regions. Several important issues warrant special attentions in design considerations. The first is elimination of a large number of parasitic collisions due to ultra small (40 cm) bunch spacing that comes with ultra-high bunch repetition frequency (750 MHz). Current detector design for MEIC requires a magnet-free space of ±4.5 to ±7 m near a collision point, and thus could bring up more than 70 parasitic collisions in a head-on collision setup. It is well known that long-range beam-beam interactions at parasitic collisions are major sources of troubles in terms of beam loss, detector background and luminosity lifetime. Following the KEK-B e+e- collider [7], the MEIC design adopts a crab crossing scheme for colliding beams to mitigate this problem. It has been shown that a crab crossing angle of 25 mrad or larger is sufficient to separate two MEIC crossing beams fast enough to eliminate all parasitic collisions. Further, it is in the MEIC baseline design that multi-cell SRF crab cavities will be developed and installed on both sides of a collision point to recover luminosity loss by restoring head-on collisions. The second issue is correction of large natural chromaticity induced by a strong final focusing. The value of natural chromaticity is, to the first order, depending on a ratio of the final focal length and value of beta-star. In the MEIC design, the natural chromaticity could be 10 even 100 times larger than the existing hadron colliders after pushing down the beta-star to a few cm. It is further amplified in MEIC compared to the e+e- colliders in the B-factories since the magnet-free space (which roughly equals the final focal length) in KEK-B and PEPII are much smaller (less than 1 m). As a key R&D topic of MEIC, a chromatic compensation block must be carefully designed such that it not only could provide adequate correction of chromaticity but also should leave a large enough dynamic aperture in order to have a good beam lifetime.

It should be pointed out that highly flat ion beams in the high energy end of ELIC may provide a real opportunity to implement a crab-waist scheme [15] for the interaction region design. Such a new scheme has already been chosen for conceptual designs of both the SuperB and Super-KEKB colliders [16, 17] after complete success of a proof-of-principle experiment at DAΦNE [18]. It is expected this scheme will help both super B-factory designs to achieve a luminosity above 10^{36} $cm^{-2}s^{-1}$. Our initial studies suggest ELIC may be also benefited by employing this scheme.

FORMATION OF MEIC ION BEAM

While the MEIC design is following the luminosity leaders, namely two B-factory e+e- colliders, to achieve ultra-high luminosity, it must be acknowledged that ion beams are different from lepton beams. First, there is no synchrotron radiation damping for ions at the MEIC or ELIC energy range. Second, it is not feasible economically to build a linac based full energy injector to the MEIC ion ring. These two differences are extremely critical not only to formation of high bunch repetition and high average current ion beams but also to the ability to reach and maintain short bunch length and small transverse emittance during the entire store and collision of ion beams. The MEIC ion complex design must take these two disadvantages into account and should make every possible effort for proper mitigation.

Staged Electron Cooling in Ion Collider Ring

A damping mechanism could be in principle introduced into the MEIC ion collider ring. The best candidate of such as we believe is staged electron cooling. As an essential part of the MEIC or ELIC design, an ERL based circulator electron cooler is proposed to deliver such ion beam cooling [19]. A staged cooling scheme means that electron cooling will be called for first at the injection energy of the ion collider ring for initial 6D emittance reduction, then at the top beam energy after boosting for conditioning the beams to the designed state for collision, and most importantly, will be utilized for continuous cooling during collisions in order to suppress intra-beam scattering heat-up and other nonlinear collective effects. Our estimations indicate that, with a proper cooling electron beam (good beam quality and 2 to 3 times the current compared to the ion beam), electron cooling efficiency is good enough to achieve the design goal stated above. Nevertheless, it must be pointed out that the damping time associated with the electron cooling is in a range of ten seconds to a minute, roughly a thousand times longer than the typical radiation damping time of lepton beams in MEIC and in B-factories. It remains an open question, and therefore presently a key R&D issue, whether the continuous electron cooling is able to help mitigate long term effects of beam-beam instabilities and to improve luminosity lifetime. Computer simulations of beam-beam effect with electron cooling up to a time scale of seconds or minutes are currently underway.

MEIC Ion Complex

Accelerating protons or ions from sources to high energies and accumulating them to a beam with even a modest current is a very slow and painful process presently, compared to the lepton beams. Commonly used synchrotron based boosters accelerate ions very slowly in comparison to a linac of the same energy boosting capacity, and thus prolong the time the non-relativistic ions spend in the space charge dominated region. The strong space charge forces at the stage of extremely low energy could cause beam emittance blow-up as well as a serious bottle-neck of accumulating ions into a bunch bucket. Like Project-X in Fermilab [20], the MEIC design calls a SRF linac to accelerate ions from sources to about 200 MeV/u. The ion energy at end of the linac is determined mainly by the constraint of machine cost. There are two booster rings after the linac to bring the ion energy from 200 MeV/u to 3 to 5 GeV/u (pre-booster or accumulation-cooler ring) and then to 15 to 20 GeV/u (large booster or low energy ring). The ion beams will be finally injected into the collider ring and be accelerated to the top energy for collision. It should be noted that all the energies given here are for a proton beam; the corresponding energies for ions (from deuterons to fully stripped leads) should be scaled proportionally by mass and charge unit of the ions. Figure 1 shows a schematic drawing of the MEIC ion complex design and roles of its major components are summarized in Table 2. The figure-8 shapes of all three rings are adopted for preserving high polarization of light ions as well as for accommodating polarized deuterons, an equally important issue of the MEIC design. However, that being out of the scope of this paper, it will not be discussed here.

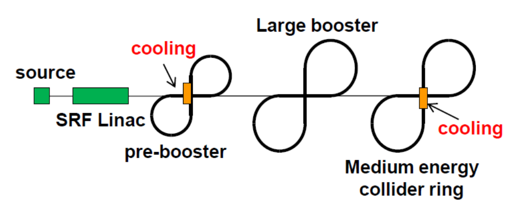

Figure 1: A schematic drawing of MEIC Ion Complex.

Table 2: Major Components of MEIC Ion Complex

	Peak Energy (GeV/u)	Cooling	Processes
Source	~0		Stripping
SRF Linac	0.2		Stripping
Pre-booster	3 to 5	DC	Accumulations
Large Booster	15 to 20		
Collider Ring	20 to 60 (100)	Staged	RF bunching

Several design goals have been set for the MEIC ion complex after careful consideration. For example, optics of all three MEIC synchrotrons, i.e., boosters and collider ring, should be specially designed such that no crossing of transition energies will be permitted for any ion species in order to prevent particle loss associated with the crossing. Electron cooling with a DC beam will also be called for at the pre-booster as a cornerstone of the design concept to help accumulation of ion beams.

Some advanced concepts have also been envisioned or are under study though they have not yet been integrated into the MEIC ion complex baseline. The first example is multiple RF frequencies in boosters and in the collider ring. In this case, ion bunches are very long in the booster rings with a low RF frequency to alleviate space charge tune shift limits at low ion energies, and the short bunch length could be achieved at higher energies in the collider ring with a ultra-high RF frequency, through either a de-bunching then re-bunching process enabled by RF frequency gymnastics, or an adiabatic bunch splitting technique [21]. This concept may also help to solve the problem of synchronization of MEIC colliding electron and ion beams at interaction points [22]. As another example, a scheme for alleviating space charge tune-shift limit at higher energy is also envisioned in which the ion beams will be kept in a round shape in most of the collider ring but will be converted to a very flat beam at interaction regions for collisions by using an emittance-exchange procedure [4].

CONCLUSIONS

In this paper we present a review of an MEIC high luminosity concept. Key ingredients of this concept are ultra-high bunch repetition frequency, very short bunch length and strong final focusing. We also discussed the impact of this luminosity concept on the interaction region design. Presently at JLab, a conceptual design of the MEIC ion complex is under development which will be responsible for producing ion beams that meet the requirement of the luminosity concept. There will be significant R&D work ahead in order to successfully implement the luminosity concept.

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