September 7, 2016

Report on eRHIC Design Development
with greatly reduced technical risk

1 Introduction

The US Nuclear Physics community has recommended "a high-energy high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of FRIB" in the NSAC 2015 Long Range Plan for Nuclear Science [1],[2]. The key machine parameters for the EIC to address the EIC science questions have been well established:

- Polarized (~70%) electrons, protons, and light nuclei
- Ion beams from deuterons to the heaviest stable nuclei
- Variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV (e-p)
- High collision luminosity ~$10^{33\text{-}34}$ cm^{-2} s^{-1}
- Possibly more than one interaction region.

Brookhaven National Laboratory has proposed eRHIC, a cost effective path to the EIC by taking advantage of the existing Relativistic Heavy Ion Collider (RHIC) facility. Inside the present RHIC tunnel an electron accelerator would be added to deliver polarized electron beam for collisions with RHIC polarized protons or heavy ions.

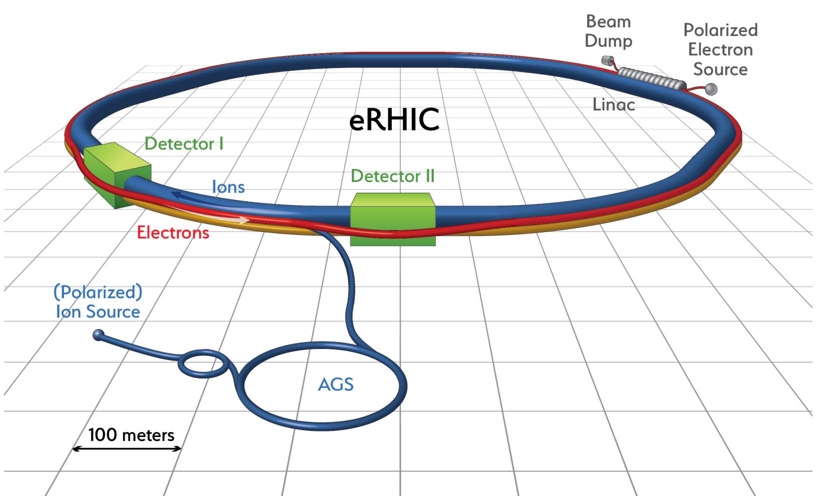

Figure 1: Schematic eRHIC layout showing the main elements for both the Linac-Ring and Ring-Ring designs. Elements from the existing RHIC facility are shown in blue, the electron accelerator using a SRF linac is shown in red, and the ring with the colliding electron beam is shown in yellow.

A layout of the eRHIC facility is shown in Figure 1. The eRHIC facility, as described in the design study of 2014 [3] and based on a high-energy, high intensity Energy Recovery Linac (ERL) for the electron accelerator and strong cooling of the hadron beam, would achieve or even exceed all of the above EIC requirements. However, for the high current polarized electron source and the strong high-energy hadron cooling, it requires extensive R&D to retire these risks. To address the issue of high technical risks, BNL has adopted a staged approach for eRHIC with an initial luminosity about a factor of 10 below the above requirement followed by a luminosity upgrade through the installation of the strong high-energy hadron cooling. This approach is, in fact, very typical for large particle colliders.

The strategy to arrive at an optimum design, which

- satisfies the initial requirements,
- has acceptable technical risk, reasonable cost and a
- clear upgrade path to achieve ultimate performance,

consists of developing, in a first step, two conceptual designs for this initial eRHIC facility, one based on an ERL electron accelerator (LR) and one based on an electron storage ring (RR) and then make an optimum choice on the path forward based on these design studies.

The initial eRHIC design aims to cover the parameters listed in the Long Range Plan including the upgraded energy reach:

- CM energy: ~ 20 - 140 GeV
- Luminosity: ~$10^{32\text{-}33}$ cm^{-2} s^{-1}; upgradable to ~$10^{33\text{-}34}$ cm^{-2} s^{-1} with modest facility upgrades depending on R&D progress for ion cooling
- Frequent changes to the spin-sign assignment of the electron and proton beam as determined by the physics requirements
- Beam divergencies at the interaction point that do not exceed the experimental limits

The design teams were given guidance about acceptable technical risk: For a design with acceptable risk, each element of the accelerator complex uses technology that has already been demonstrated in an equivalent parameter regime in other applications. An equivalent parameter regime in this context refers to any usage, which requires extrapolation by less than a factor of two if the comparison is straightforward. While certain aspects of the design may not lend themselves to this degree of clarity, the guiding principle should still be that the design should rely on proven technology. More complicated arguments than the most straightforward extrapolation will need to be supported by clear documentation of the underlying technology maturity.

Both designs incorporate a number of common requirements and limits. In addition to established beam dynamics limits, such as maximum beam-beam parameter (hadron ≤ 0.015; electron for RR ≤ 0.1) and space charge parameter (≤ 0.06), the EIC science program requires specific design parameters. A robust physics program aimed at exploring the novel phenomenon of gluon saturation requires that the CM energy range of an electron-ion collider extends to 90 GeV in electron-nucleus collisions (140 GeV for e-p). The designs also need to allow for the detection of forward scattered protons with a transverse momentum between 0.2 and 1.3 GeV/c. This latter requirement limits the maximum proton angular spread at the collision point in at least one plane.

Below, and in more detail in the appendices, the outline for the two designs (LR and RR) will be given. Figure 2 shows the peak luminosity vs. CM energy for the low risk LR and RR designs as well as the luminosity-upgraded, ultimate eRHIC design, overlapped with the areas of the EIC science program. Table 1 lists the main parameters of the designs for the beam energies with the highest peak luminosity. Considered as electron-nucleon luminosity, similar luminosity levels are achieved in electron-ion collisions.

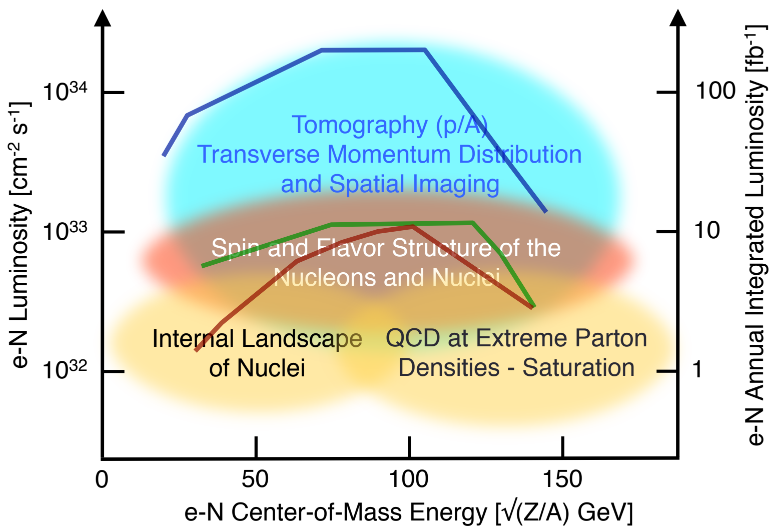

Figure 2: eRHIC peak luminosity versus CM energy for the Low Risk Linac-Ring (green), the Ring-Ring (red) and the ultimate eRHIC (blue) design.

The luminosity calculation includes factors related to the hourglass effect and, for the LR design, to the electron pinching effect at collision. The high luminosity of the RR design is achieved mainly due to high electron and proton currents circulating in storage rings. The high luminosity of the LR designs is largely due to small beam sizes at the interaction point.

Table 1: Beam parameters at the point of highest luminosity of e-p collisions for the eRHIC design options.

	RR design		Low Risk LR design		LR Ultimate design	
	e	p	e	p	e	p
Energy [GeV]	10	250	13	275	8.3	250
CM energy [GeV]	100		105		91	
Bunch frequency [MHz]	28.2		9.4		9.4	
Bunch intensity [10^{10}]	31	12	3.3	30	3.3	30
Beam current [mA]	1300	500	50	415	50	415
rms norm.emittance h/v[um]	484/77	4.7/1.8	64/64	1/1	16.5/16.5	0.27/0.27
rms emittance h/v [nm]	24.2/3.86	17.7/6.7	2.5/2.5	3.4/3.4	1.0/1.0	1.0/1.0
beta*, h/v [cm]	416/7.4	566/4.2	35/17.5	26/13	7/7	7/7
IP rms beam size h/v [um]	318/17		30/21		8.4/8.4	
IP rms ang. .spread h/v [urad]	80/230	57/400	85/120	115/163	120/120	120/120
max beam-beam parameter	0.1	0.015	1.0	0.004	4.1	0.015
e-beam disruption parameter	Neglig.		6		36	
max space charge parameter	4e-5	0.002	9e-5	0.004	8.6e-4	0.058
rms bunch length [cm]	0.8	8	0.3	16	0.3	5
Polarization [%]	80	70	80	70	80	70
Peak luminosity [$10^{33}cm^{-2}s^{-1}$]	1.1		1.2		14.4	

For any high luminosity Electron-Ion Collider the interaction region needs to provide fast beam separation to avoid parasitic collisions and also carefully manage electron synchrotron radiation to protect the detector systems. This requires a beam crossing angle at the collision area. The LR design needs14 mrad and the RR design needs 22 mrad.

In order to preserve the luminosity in the IR with these crossing angles a crab-crossing scheme is adopted. Crab crossing was already used to increase the luminosity of the electron-positron collider KEKB but not yet in hadron colliders, which represents a risk for any Electron-Ion Collider. However, crab crossing is planned for the high luminosity upgrade of the proton-proton collider LHC. The choice of eRHIC SRF crab-cavity design and parameters is heavily based on the LHC design. A beam test with two crab-cavity prototypes is planned at the SPS at CERN.

2 Low Risk Linac-Ring Design

The Linac-Ring (LR) design approach employs electrons that are accelerated in re-circulating energy recovery linacs (ERL), which then collide with the ion beam just once. Such an approach removes the limitation on luminosity of the beam-beam effect of the high-energy hadron beam on the lower energy electron beam. This opens a potential path to higher luminosity by using smaller transverse beam sizes at the collision point. The LR design operates with a low electron beam current and therefore produces only a modest amount of synchrotron radiation making it a highly energy efficient facility.

The main elements of the LR eRHIC design are:

- A high intensity polarized electron source and injector
- A high intensity, multi-pass Energy Recovery Linac in the RHIC tunnel
- A high luminosity interaction region with spin rotators that allows for a full acceptance detector; a second interaction region is possible.

The technical risks of this design are greatly reduced compared to the original ultimate eRHIC design by

- replacing the 50 mA polarized electron beam from a single gun with beams from 8 separate 6.25 mA guns merged with RF deflectors,
- eliminating the initial need for strong, high energy hadron cooling and using the 1 μrad transverse beam emittance available from the RHIC injector
- replacing the FFAG permanent magnet recirculation loop with conventional electro-magnet beam lines,
- and using only the existing technology of beam line Higher Order Mode dampers for the SRF CW linac.

Successful R&D towards high intensity polarized electron guns, FFAG permanent magnet beam transport and wave-guide HOM dampers would allow for substantial reductions of $200 – 300M of the eRHIC project cost.

The successful development of strong high-energy proton cooling, such as Coherent electron Cooling, will open a clear path to a luminosity upgrade. The Linac-Ring approach strongly benefits from the hadron cooling as the luminosity scales as inverse of square of the transverse emittance. With cooling rates expected from the Coherent electron Cooling technique the Ultimate design luminosity exceeding 10^{34} cm^{-2} s^{-1} can be achieved.

Appendix I presents the detailed accelerator design of the Low Risk LR design.

3 Ring-Ring Design

In the Ring-Ring (RR) design approach the high intensity electron beam is stored in a storage ring. The Ring-Ring option with luminosities of 10^{32-33} cm^{-2} s^{-1} can cover the whole energy range of the EIC science case. The design does not require hadron cooling to achieve this luminosity level.

The main elements of the RR eRHIC design are:

- A full energy polarized CEBAF-like injector in the RHIC tunnel
- A high intensity, spin-transparent electron storage ring in the RHIC tunnel
- A high luminosity interaction region with spin rotators that allows for a full acceptance detector; a second interaction region is possible.

This design is mainly using established and existing technologies from the high intensity electron storage rings of the B-factories for the eRHIC electron storage ring and from CEBAF for the electron injector.

The Ring-Ring design could be upgraded, using strong hadron cooling, by halving of the bunch charges, bunch lengths, emittances and betas, and by a further doubling of the number of bunches, which provides a maximum luminosity of 1.2 x 10^{34} cm^{-2} s^{-1}. This is described in the Appendix II.

If a 650MHz SRF linac were used, similar to the one for the ERL in the LR design, upgrading to the Ultimate ERL-Ring scheme would then require additional recirculation loops and wave-guide HOM dampers. These upgrade modifications would need to be anticipated in the initial design.

Appendix II presents the detailed accelerator design of the Low Risk RR design.

4 Future Plans

At an extraordinary meeting of the eRHIC Accelerator R&S Advisory Committee the plans for the development of both the low risk LR and the RR eRHIC designs were reviewed with the charge to evaluate whether the technical risks of the designs could be deemed acceptable, according to the definition given above, by the end of 2017.

The Committee concluded that this is feasible for both designs with a concerted effort to address a number of issues:

- Both design studies need to continue to reach a higher level of maturity and complete detailed simulations that the level of beam-beam interaction, dynamic aperture, and beam halo formation is acceptable.

- For the LR design the most important R&D item is the high intensity polarized electron gun complex. A plan for the development of one of the eight high current and high bunch charge electron guns exists and should be followed. Integration of several guns into a single injector is foreseen as an integral part of the future R&D effort towards realization of the LR design.

- For the RR design simulations of the polarization lifetime have to be completed and the detector backgrounds from the high level of synchrotron radiation need to be evaluated.

With these questions resolved to a satisfactory degree, we intend to either select or combine the two design concepts into a single eRHIC design proposal and to decide on an upgrade path for ultimate performance.

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[1] "The 2015 Long Range Plan for Nuclear Science", http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf
[2] "Electron Ion Collider: The Next QCD Frontier" (EIC White Paper), arXiv:1212:1701, (2014)
[3] E.C. Aschenauer, et al., "eRHIC Design Study: An Electron-Ion Collider at BNL", arXiv: 1409:1633, (2014).