# ERL-RING AND RING-RING DESIGNS FOR THE RHIC ELECTRON-ION COLLIDER *

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*Abstract*

Two design options explored for eRHIC accelerator design are described: the ERL-Ring and the Ring-Ring. Both are capable to provide the luminosity level ($10^{33}$ $cm^{-2}s^{-1}$) required for an eRHIC Initial stage. Both options are upgradable to the Ultimate ERL-Ring design ($L \sim 10^{34}$ $s^{-1}cm^{-2}$). Present status of eRHIC R&D program is reported.

## FROM RHIC TO ERHIC

RHIC collider at BNL has been operating from beginning of the century with heavy ion and polarized proton collisions in several experiments. The collider has been successfully fulfilling the physics goals it was built for. Experiments with heavy ion collisions led to a discovery and consequent detailed study of properties of quark-gluon perfect fluid matter, a substance existed at the very origin of the Universe. And, using collisions of polarized proton beam, the study of proton spin composition has been carried out, especially, gaining the knowledge of a gluon component of the proton spin. Besides producing remarkable nuclear physics results the RHIC collider has demonstrated consistent improvements in the machine luminosity of both heavy ion and proton collisions, literally every year. Presently, RHIC is an only place in the world with high energy polarized proton beams. It employs numerous techniques and devices throughout the injector chain and in RHIC itself to achieve high proton polarization level (up to 60%) of colliding beams at the store energy.

Present plan is to continue the experiments with heavy ion and polarized proton collision at RHIC till 2024. After that a transition to eRHIC, an electron-ion collider (EIC), can be realized. Recent US Nuclear Physics Long Range Plan [1] recommended a high-energy high-luminosity polarized EIC as the highest priority for a new NP facility construction. The transition from RHIC to eRHIC includes adding an electron accelerator to the existing RHIC ion complex. Building the EIC at BNL has a compelling advantage of using available $2.5B RHIC ion complex. Besides the existing ion machine, eRHIC will re-use the existing infrastructure: RHIC tunnel and buildings, detector halls and cryogenic facility. eRHIC will take a full advantage of present capability of RHIC to provide polarized protons (up to 275 GeV) and heavy ions (up to Uranium).

The physics goals of the proposed electron-ion collider are well described in the EIC White paper [2], the eRHIC Design study report [3], as well as in a EIC physics presentation made at this conference [4]. One major area or the EIC physics is related with 3D nucleon imaging and with completely resolving the nucleon spin puzzle. For these studies the high luminosity of polarized electron on polarized proton collisions is required. Other major direction of EIC exploration is related with studies of a dense gluon matter, ideally, discovering a predicted gluon saturation state, color-glass condensate. These studies are most effectively done with electron - heavy ion collisions with high center-of-mass energy (but, not necessarily requiring high luminosity).

Reaching into the gluon saturation conditions calls for highest eRHIC electron energy to be 18 GeV. In the same time the experiments require wide coverage of center-of-mass energy range, so that the electrons must be provided in the range from 5 GeV to 18 GeV. Other collider design goals are:

- Reaching L $\sim 10^{33}$-$10^{34}$ $cm^{-2}s^{-1}$ (exceeding HERA luminosity by 2 orders of magnitude).
- Providing high electron and proton polarization (>70%). Realizing complex spin pattern on the same fill.
- Satisfying full (or near full) acceptance detector, with detector elements integrated in the accelerator IR for forward particle detection.
- Minimizing the construction and operational cost of accelerator.

## TWO ERHIC DESIGN OPTIONS

To achieve the accelerator design goals two design options are being evaluated, accordingly to a type of electron accelerator employed. An ERL-Ring design option uses an energy-recovery linac for electron beam acceleration. Alternative design option, Ring-Ring, considers storing high current electron beam in a storage ring.

The luminosity of ERL-Ring design is not limited by the electron beam-beam limit. This design option provides a straightforward way to high luminosity by using a small beam size at the interaction point. Application of a hadron cooling provides a simple possibility to increase the luminosity even further. This design option is also more efficient in terms of construction and operation cost. On the other side it calls for some accelerator technology beyond the present state-of-the-art, especially demanding high current polarized electron source.

The Ring-Ring design has less technological challenges than the ERL-Ring one. High luminosity is achieved by utilizing high circulating beam currents. Large synchrotron radiation power, produced by high electron current,

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has to be dealt with in experimental detectors and as a considerable factor in collider construction and operation costs.

Figure 1 shows required luminosities for major areas of eRHIC physics as well as intended performance of different design options. Initial planned performance of eRHIC is intended to be at the luminosities corresponding to so-called Initial designs. The Initial ERL-Ring design uses 1 MW limit for the synchrotron radiation power and 50 mA limit for polarized electron source current. Initial Ring-Ring design assumes 10 MW maximum power of synchrotron radiation. Both Initial designs do not include the proton beam cooling. In the same time for heavy ions both design options can use the stochastic cooling system of present RHIC. The Ultimate design demonstrates the luminosity level achievable by applying strong hadron cooling. The cooling rates required for the Ultimate design can be achieved using novel technique of Coherent electron cooling, presently pursued as an important R&D [5]. Both Initial design options should have a possibility of the upgrade to the luminosity level of the Ultimate design.

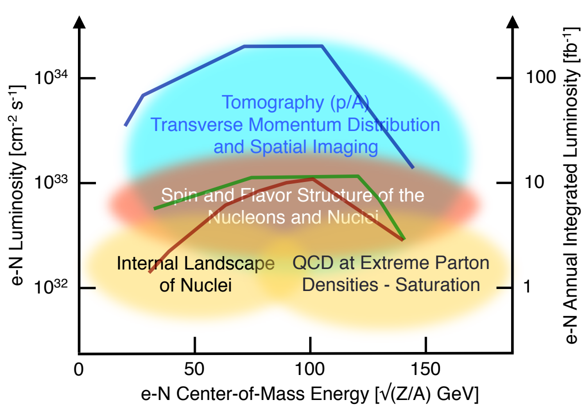


Figure 1: Luminosity vs CME of various considered eRHIC designs overlapped with eRHIC physics areas. Green curve- Initial ERL-Ring design, red curve - Initial Ring-Ring design, Blue curve- Ultimate ERL-Ring design.

## *ERL-Ring Design Option*

This design option stems from experience and technology of re-circulaitng electron linacs (12 GeV CEBAF) and high current energy-recovery linacs (ERLs at Jlab and BINP). The general layout is shown in Fig. 2. The electron beam is accelerated in a superconducting linac. With 6 re-circulation loops, located in the RHIC tunnel, the maximum energy of 18 GeV can be reached. The electron beam passes a collision point just once, allowing for very strong collision (no standard beam-beam limit storage rings) and high luminosity. After the collision the energy of electron beam is recovered by deceleration in the same linac, allowing to maintain sufficiently high average electron current (up to 50 mA). No proton cooling is required for the Initial design. The luminosity upgrade to the Ultimate design is done by implementing a strong hadron cooling system.

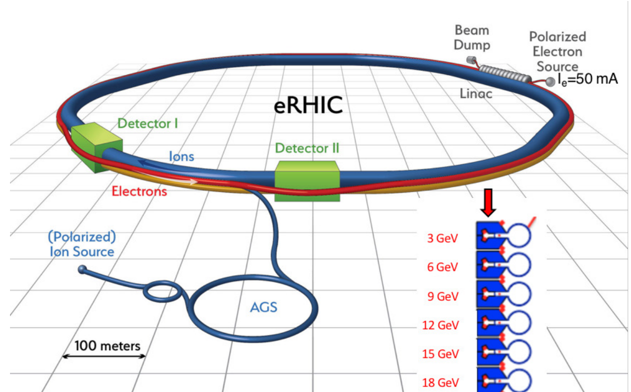


Figure 2: The ERL-Ring design option layout.

The main linac consists of 647 MHz SRF 5-cell cavities. Total of 142 cavities are required in the present design. The frequency of main linac accelerating cavities is benefitting from the 650 MHz SRF development program for the Fermilab PIP-II project [6]. Similar to Fermilab cavity requirements, eRHIC cavities are expected to produce 18 MV/m gradient at $Q_0$= 3E10. But in addition to that, an efficient HOM damping system has to be implemented in eRHIC cavities. The HOM loss power evaluated for eRHIC electron beam parameters in frequency range up to 40 GHz is 7 kW. This amount of power can be absorbed using room temperature ferrite or SiC beam-pipe dampers, following experience in storage rings at KEKB and Cornell University [7,8]. eRHIC cryo-module contains two cavities and is surrounded by two SiC absorbers. The cavity design has been developed and optimized for HOM impedances. Multi-pass BBU studies has been performed, verifying that design electron beam current is stable at multiple re-circulations through the main linac.

Some of the technology utilized in the ERL-Ring design is beyond of present state-of-the-art. The design intends to bring the ERL technology from sub-GeV electron energies into 10-20 GeV energy area. High beam power passing through the accelerator requires an exceptional control of beam losses and good knowledge of possible sources of beam halo. Collimation techniques may be employed to address the halo produced by the injector.

But, a biggest technological challenge is seen in producing large 50 mA average polarized electron current from an electron source. The current of 4 mA was demonstrated in JLab studies with the cathode lifetime of 5.5 hours [9]. The JLab gun design can be improved to use a larger cathode with implemented cathode cooling, which is more suitable for high charge bunch production (the bunch charge of 5.3 nC is required for eRHIC). To achieve the 50 mA current, 8 such guns, each producing 6.3 mA, can be used together with a merging system which combines the current from all guns. The design of the polarized source based on eight electron guns and the merging system has been developed, which uses several deflectors operating at the frequencies from 1.2 MHz to 4.7 MHz. The beam transport through the injector is being optimized using simulations. In addition, experimental studies are underway to explore possible high bunch charge issues at bunch extraction from cathode and the cathode lifetime dependencies. A prototype gun, intended to produce up to 7 mA current, is being designed and will be built next year. On longer time scale the R&D effort for a single electron gun able to produce 50 mA polarized current will continue.

The electron beam polarization produced at the source will be at the level 85-90%. Having the polarization oriented in the injector (using a Wien filter) to the vertical direction, one expects easy polarization preservation during the acceleration. A spin rotator, based on combination of solenoidal and dipole magnets, transforms the polarization to the longitudinal at the interaction point.

### *Ring-Ring Design Option*

The Ring-Ring design is based on high current electron storage ring technology (B-factories) and the colliding beam performance in lepton and proton colliders. The layout of the accelerator is shown in Fig. 3 [10]. The layout looks quite similar to one of the ERL-Ring design, except only three beamlines are used. Two of them serves as recirculation loops for the injector linac, and third one presents the storage ring. The injector linac operating in pulsed mode provides 6 GeV/turn acceleration. With the injector linac based on 647 MHz cavities, such design layout allows for a straightforward future upgrade to the high luminosity Ultimate ERL-Ring design. Although, alternative, less expensive, option of the injector based on XFEL/LCLS-II type cryo-modules is also possible.

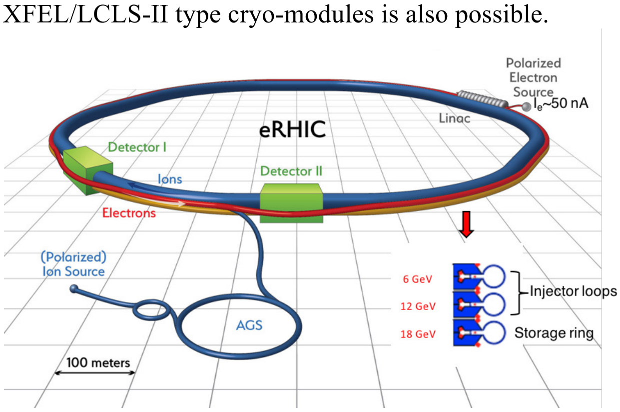


Figure 3: The Ring-Ring design option layout.

The luminosity in this approach is defined by allowed synchrotron radiation power (accepted limit at 10 MW) and the beam-beam parameter limits ($\xi_p$ < 0.015, $\xi_e$ < 0.1), following experience of KEKB and RHIC. The resulting linear SR power load is about 4 kW/m, which is twice lower than one demonstrated in B-factories. In order to enhance radiation damping at lower electron energies (below 11 GeV) and, hence, increase achievable beam-beam parameter the split structure is used for arc dipole magnets (Fig. 4) [11]. At lower electron energies the central section of the arc dipole is powered to produce strong opposite sign field creating an effective wiggler for enhancing radiation damping.

Another wigglers (Robinson type) are located in a straight section of the electron ring, providing the control of electron emittance. This is necessary tooling for matching electron and ion beam sizes at the IP at different energies.

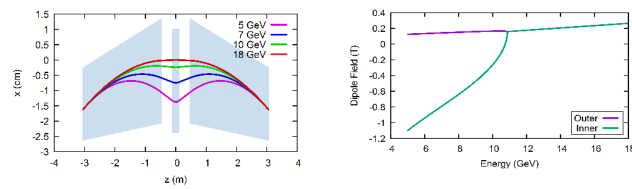


Figure 4: The split arc dipole layout with electron orbits at different energies (left plot) and the outer and inner section magnetic field vs the beam energy (right plot).

In the ion ring the number of bunches must be tripled from presently used in RHIC. This will require the injector system upgrade. Also, to reduce the resistive heating the present cold pipe of ion ring must be copper-coated. A technique for in-situ pipe coating is being developed, involving a magnetron coating mole. With 36 ns bunch spacing the electron cloud and associated heat load must be carefully evaluated. With the respect to the electron cloud the experience and observations from recent LHC runs are very valuable [12].

Proving that high electron polarization level (more than 70%) can be maintained at electron energies as high as 18 GeV presents one of challenges for this design option. Following experience of high energy polarized electron storage rings, such as HERA, PETRA and LEP, achieving high polarization involves highly efficient orbit control (including possibility of BPM-to-quad center beam-based alignment), well controlled betatron coupling and implementation of harmonic spin matching. For spin rotators and detector solenoids the set of spin matching conditions on lattice functions has to be satisfied. The spin simulation studies intended to verify the depolarization time in the presence of misalignment and magnet errors have recently began.

Beam polarization requirements determines major injector features. In order to provide a complex spin pattern, with different bunches having the polarization up and down on the same fill, a full energy injector is required. And the depolarization time defines the rate of replacing individual bunches. At worst case, at 18 GeV, 1 Hz bunch replacing rate is required rate to keep the average polarization level above 70%.

## INTERACTION REGION FEATURES

The design of interaction region is significantly impacted by detector requirements for forward acceptance of neutrons and scattered protons, as well as by managing protection of detector area from synchrotron radiation and related background. It leads to necessity of using crab-crossing scheme and very special IR magnet designs. IR detector elements, such as, Roman Pots and ZDC, have to be integrated at proper locations among interaction region magnets.

Crossing angles of 14 and 22 mrad are used in the ERL-Ring and Ring-Ring designs, correspondingly. To prevent the luminosity decrease, crab cavities are used for ion beam with frequencies ranging from 140 to 340 MHz. A crab cavity based on double quarter wave resonator principle has been developed in BNL for the LHC luminosity upgrade. A prototype of such cavity has been built and is going to be tested with beams in SPS. The eRHIC crab-cavities will be based on the same design approach.

Hadron superconducting IR magnets must have large enough aperture in order to propagate forward neutrons and protons to detector elements (Roman Pots and ZDCs) located downstream. Also, an electron beam pass through the hadron SC magnets must be arranged. Two design approaches for the IR magnets are shown in Fig. 5. In the ERL-Ring design "sweet spot" concept was proposed which arranges a field-free electron pass between superconducting coils [13]. For the Ring-Ring design an active shielding technique developed for ILC IR magnets is used. In this method an outer coil is added to have magnetic flux contained from reaching the electron orbit area [14].

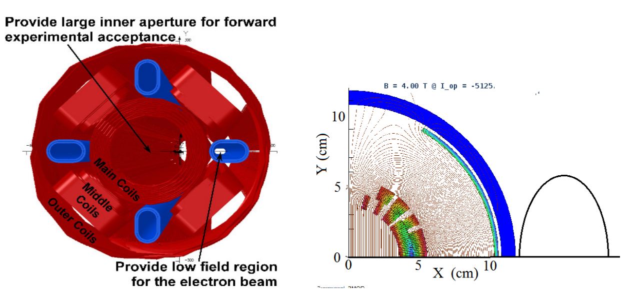

Figure 5: IR magnet design developed for eRHIC. "Sweet spot" design (left plot), and the active shielding design (right plot).

## ERHIC R&D PROGRAM

The eRHIC R&D program is underway on three directions: R&D for the Initial designs, the cost reduction R&D and the R&D for higher luminosity.

The R&D for the Initial design aims to resolving all remaining accelerator physics issues and technological risks for both ERL-Ring and Ring-Ring Initial designs with the luminosity ~ $10^{33}$ cm$^{-2}$ s$^{-1}$. For the ERL-Ring design option the crucial R&D is related with developing the polarized electron source based on merging scheme. In the same time many of R&D items are similar, or even common, for both design options. Most important include simulation work on beam-beam effects; advancing methods for in-situ copper-coating of RHIC beam pipe; developing crab-cavity prototypes and studying beam dynamics with crab-cavities; realizing polarized $^3$He production and acceleration.

Considerable R&D efforts are linked to developing technologies which may substantially reduce the accelerator construction and operation cost. This cost reduction R&D is for the ERL-Ring design option where several technological opportunities are present to decrease the cost. One of them is related with advancing HOM power dampers based on waveguides. Although the HOM waveguide damper technology has been developed for many years in Jlab, it is not considered yet as fully proven. BNL is presently developing an approach based on ridge waveguide configuration for HOM dampers for 650 MHz cavity [15]. Funded by the laboratory R&D funds, a cavity prototype together with waveguide dampers will be built and tested on two year scale. Applying the waveguide dampers, in addition to the beam-pipe absorbers, will allow to significantly reduce the total length of the eRHIC main linac.

Another cost reduction opportunity is related with implementing an FFAG version of recirculating loops. The FFAG technology has been used so far mostly for sub-GeV proton accelerators. The EMMA NS-FFAG test accelerator operated with electron beam. A beamline based on the FFAG approach is capable to transport, in the same time, beams in wide energy range (the ratio of maximum to minimum energy can be as large as 4). Thus it looks a natural approach for reducing the number of recirculation loops. The FFAG-based lattice was thoroughly investigated for the ERL-Ring design option, and it was established that only two FFAG beamlines are needed to accelerate electrons up to 21 GeV [16]. In addition, the FFAG beamlines can be realized using permanent magnets. Different permanent magnet designs (Hybrid-type, Halbach) were developed and several prototypes of those magnets were built [17].

An ultimate test for the FFAG recirculation pass technology with respect to eRHIC will be made at the Cornell university where multi-pass FFAG-based ERL test facility (CBeta) is being constructed [18]. The CBeta will accelerate the electron beam up to 150 MeV in 4 re-circulations. These re-circulations will be realized only by one FFAG beamline, based on permanent magnets. The CBeta facility takes advantages of existing high-current injector (up to 100 mA current is planned) and existing SRF linac (1.3 GHz) with design energy gain 36 Mev/pass. The beam test are expected in 2018-2019.

Although the baseline ERL-Ring design utilizes the polarized source based on merging scheme, the R&D effort will continue towards producing 50 mA current from a single gun. On this path two possibilities are being explored: a Gatling gun (multiple cathodes in a same vacuum vessel) and a large cathode gun.

Potential savings for the ERL-Ring design due to the successful cost reduction R&D are on the scale $200-300M.

Realizing the luminosity upgrade to at least $10^{34}$ cm$^{-2}$s$^{-1}$ level at a later stage is the firm goal of the eRHIC collider design. Such upgrade, called the Ultimate design, requires strong transverse and longitudinal cooling of high-energy proton beam. Novel technique of coherent electron cooling (CeC) is considered as capable to provide the strong cooling with cooling rates on scale of tens of minutes, or even minutes. The Proof-of-Principle experiment is underway on RHIC using constructed test facility, which includes electron beam accelerator (SRF gun+20 MeV SRF linac) and transport lines, as well as helical wigglers in a section common for gold ion and electron beams. So far, the electron accelerator was commissioned, extracting the bunch charge as high as 3 nC from the 1.7 MeV SRF gun, and demonstrating the electron beam transport from the gun to the dump [5,19]. The cooling studies will be carried out in 2017.

An interesting development, that can also benefit the eRHIC accelerator design, is a proposed test for ERL operation at CEBAF, which can be performed at the beam energy as large as 8 GeV [20].

## CONCLUSION

The eRHIC accelerator design covers the complete EIC White Paper science case and is highly cost effective. Two design options are presently considered. The ERL-Ring eRHIC design option combines high performance with high energy efficiency. The Ring-Ring eRHIC design, operating at the beam-beam limit, reaches high performance using mostly existing technology.

Cost effective, reduced technological risk Initial ERL-Ring and Ring-Ring eRHIC designs with required energy coverage and $10^{33}$ $s^{-1}cm^{-2}$ luminosity form a basis for eRHIC project proposal. Cost effective upgrade to ~ $10^{34}$ $s^{-1}cm^{-2}$ luminosity Ultimate ERL-Ring design is possible for both design options.

Focused eRHIC R&D addressing all critical technical risks and design issues is underway and must be realized over the next 2-3 years.

## ACKNOWLEDGMENT

eRHIC design development described in this paper is a result of successful work of a large team of BNL accelerator scientists and engineers (more than 50 people). I also want to appreciate increasing contributions to the eRHIC R&D studies from other laboratories and universities over the world, most notably from Cornell, LBNL, JLab, ANL, MIT and CERN.

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