COMPUTATION REQUIREMENT TOWARDS THE FUTURE ELECTRON ION COLLIDER, eRHIC[*]

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Abstract

eRHIC is the proposed electron ion collider(EIC) in Brookhaven National Laboratory, an upgrade of RHIC, the only operating collider in US. The demand of high luminosity (10^{33} to 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) impels the adoption of an innovative linac-ring collision scheme, i.e. an ERL as the new electron accelerator. The design of eRHIC requires detailed numerical studies on various aspects, which include the start-to-end tracking of multi-pass ERL, special beam-beam study of linac-ring scheme, various beam dynamics issues, spin tracking, novel orbit/optics correction scheme. We will review the eRHIC simulation studies and discuss the challenges of the precise numerical modeling, in order to reduce the design risk.

INTRODUCTION

Electron-ion collider is a power tool of deep inelastic scattering for probing the inner structure of the hadrons. To get a much greater insight of the nucleon structure, including the distribution of the momentum, spin and flavor of the quarks and gluons, a high luminosity electron ion collider (EIC) is required.

In an EIC, the ion beam is accelerated to desired energy and stored in an synchrotron ring, while the electron accelerators has two options. An electron storage ring, together with its injector and booster, can be built and form a 'ring-ring' collision scheme with the ion ring. Alternatively, an energy recovery linac (ERL) can serve as electron accelerator, and form a 'ERL-ring' scheme. In an ERL, the electron beam gain energy from the RF cavities (usually superconducting) with the accelerating phase. After the electron beam collides with the ion beam, it will be decelerated in the same RF cavity, with the decelerating phase which is ensured by the pass length of the electron beam. The energy is then used to accelerate the new electron bunches. This energy recovery process enables high collision rate, hence high luminosity. Therefore in an ERL based collider, the electron beam is always fresh, however, its energy is re-used.

eRHIC [1] is the upgrade of RHIC, the only operating collider in US. RHIC provides up to 250 GeV proton and 100 GeV/n heavy ion. The new electron accelerator will provide polarized electron beam up to ~20 GeV. The ERL-ring scheme of eRHIC is the baseline design of eRHIC, since it has several benefits over a 'ring-ring' counterpart, which include:

- The beam-beam limit of the electron beam is removed due to a single collision for every electron bunch, which leads to an higher luminosity. The ERL-ring scheme eRHIC will achieve 4×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity from collision of 250GeV proton and 15.9 GeV electron beam.
- The electron can be dumped at a much lower energy,
- The simpler synchronization of the electron beam with various ion energies.
- Much less synchrotron radiation power

eRHIC ERL adopts a multi-pass ERL design to save cost on the expensive Superconducting RF structure, i.e. the electron beam passes the linac with accelerating phase several times to accumulate energy before collision. To avoid building large number of energy recirculation passes, eRHIC also takes advantage of the concept of FFAG [2], which has enormous momentum acceptance (up to 4x in the design), to reduce the number of recirculation beamline to two lines. The FFAG based ERL reduce the cost of the transport lines significantly. Table 1 lists the baseline parameter of ERL-ring eRHIC and the Figure 1 shows its layout.

Despite the advantages of the ERL-ring scheme, it also presents a higher risk, which includes

- The electron beam current has to be provided from the source. Therefore a 50mA polarized electron source has to be demonstrated.
- Multi-pass high energy ERL with FFAG transport and related beam dynamics.
- The new beam-beam effect in ERL-ring scheme.

Table 1: The Baseline Parameters of ERL-ring eRHIC

Parameters	eRHIC	
	e	p
Energy (GeV)	15.9	250
Bunch spacing (ns)	106	
Intensity, 10^{11}	0.07	3.0
Current (mA)	10	415
rms norm. emit. (mm-mrad)	23	0.2
$\beta^*_{x/y}$ (cm)	5	5
rms bunch length (cm)	0.4	5
IP rms spot size (μm)	6.1	
Beam-beam parameter		4×10^{-3}
Disruption parameter	36	
Polarization, %	80	70
Luminosity, 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	4.9	

Besides the experimental R&D efforts, detailed simulations of the ERL-ring eRHIC are the best tool to retire the design risks. We will present the current simulation progress and the necessary improvements in the future.

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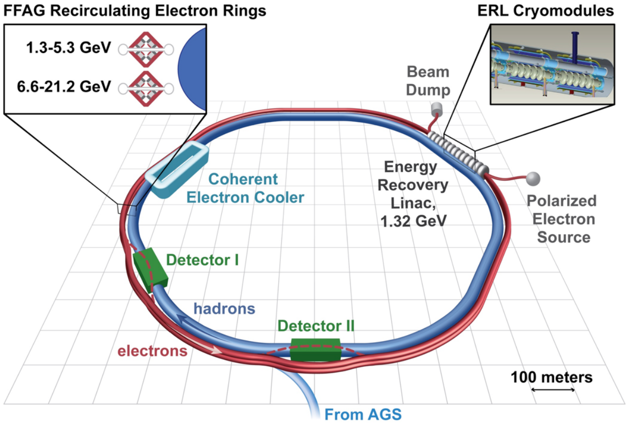

Figure 1: The layout of ERL-ring scheme eRHIC, the blue ring represents the existing RHIC ring and red ring represents the FFAG transport lines.

eRHIC ERL DESIGN OVERVIEW AND START-TO-END SIMULATION

eRHIC ERL adopts a multi-pass (12 or 16 passes) design to reach the desired collision energy of the electron beam (15.9 GeV or 21.2 GeV). It adopts a 1.322 GeV main linac, including the second harmonic cavity for energy loss compensation and optional fifth harmonic cavity for energy spread compensation. The electron beam will pass the linac 24 or 32 times before it is transported to beam dump. To avoid large number of recirculation passes, two non-scaling FFAG recirculating passes are designed to accommodate all the energies. The non-scaling FFAGs use simple FODO like cells with two shifted quadrupoles. Electron beams with different energies has different orbits with smaller orbit deviations, different optics functions and time of fight, compare with the scaling FFAGs.

The FFAG cells has to be optimized for the application as the recirculating passes of the multi-pass ERL. The optimization includes:

- Minimized the total synchrotron radiations,
- Small orbit deviations to simplify the magnet design,
- Control the chromaticity.

Two FFAGs is planned to accommodates all the energies of up-to-16-pass ERL. The first FFAG covers the first four energies and the second covers the rest of the energy. The particle with this energy takes the reference orbit , which is roughly circular in the arc. The orbit and optics of different energies are shown in the top sub-figures of Figure 3. The tune for each energies are kept in the lower half range of 0.0-0.5 to reduce the chromaticity for the lower energy passes in the FFAG, as shown in the bottom left of the Figure 3. The energy dependence of pass length and the compaction factor are shown in the bottom middle figure. The choice of the reference energy of the FFAG lattice, counterintuitively not the highest energy, optimizes the total radiation power of all energies. The radiation power dependence on energy largely differs from the fourth power of energy dependence, since the local radius is different for all energies.

To modify the curvature of the FFAG baselines, the offsets of the quadrupoles in certain cells of the FFAG (named transition cells) can be changed adiabatically. Therefore the FFAG recirculating passes can fit into the existing RHIC tunnel, which does not has unique curvature. Since we can only use finite number of cells to make the curvature transition, the fine-tuning using the dipole corrector of each magnet is necessary to reduce the residue orbit errors of each energy due to the curvature transition.

A pair of splitter and combiner are required to connect the ERL recirculating passes to the linac. They are designed to fulfill the following tasks:

- Transport the beam between the recirculating pass and the entrance/exit linac,
- Match the optics of each pass to the linac,
- Adjust the time of flight of each energy so that proper acceleration and deceleration can be achieved,
- Play important role in orbit correction.

The splitter and combiner are needed for all multi-pass ERL designs, since the task 1 and 2 are common. The task 3 and 4 are special for the FFAG recirculating passes which make its splitter and combiner more complicated. A 16-line spreader and combiner design is finished for eRHIC to fulfill those requirement, the geometric design of the splitter/combiner is shown in Figure 3.

It is the first time that FFAG-based multi-pass ERL is proposed. Therefore, no existing simulation packages can directly simulate the whole accelerating and decelerating processes, i.e. a start-to-end simulation. There are multiple beam dynamics issues to be addressed in the simulation, such as the longitudinal and transverse dynamics with various wake fields and the synchrotron radiation effects, the beam break-up studies with undamped cavity HOMs and the spin tracking to ensure the polarization at the interaction point. In addition, the correction scheme for such machine does not exist and need special treatments.

To address the above needs, we implement a python commander layer to coordinate the ERL start-to-end simulation, while use the existing and well-tested beam dynamics codes for individual beam-dynamics tasks. In one hand, the python layer collect the lattice of each parts and connect them in the start-to-end order and form a 120-km long lattice. Each individual magnet gets unique name and the errors of the each magnet are associated to it's name, which guarantees the bunch experiences same element errors when it travels through multiple times. On the other hand, the python layer does not perform the actual tracking work. It rewrite the lattice to various format of inputs and using existing code to track the macro-particles. For instance, ELEGANT [3] is used for 6-D particle tracking with wake-fields, CSR effect and the synchrotron radiation effect; Zgoubi/PyZgoubi [4] is used for start-to-end spin tracking; and GBBU [5] is used to evaluate beam current threshold of the transverse beam break-up instability. The new algorithm of the orbit and optics correction will be also implemented in the python layer.

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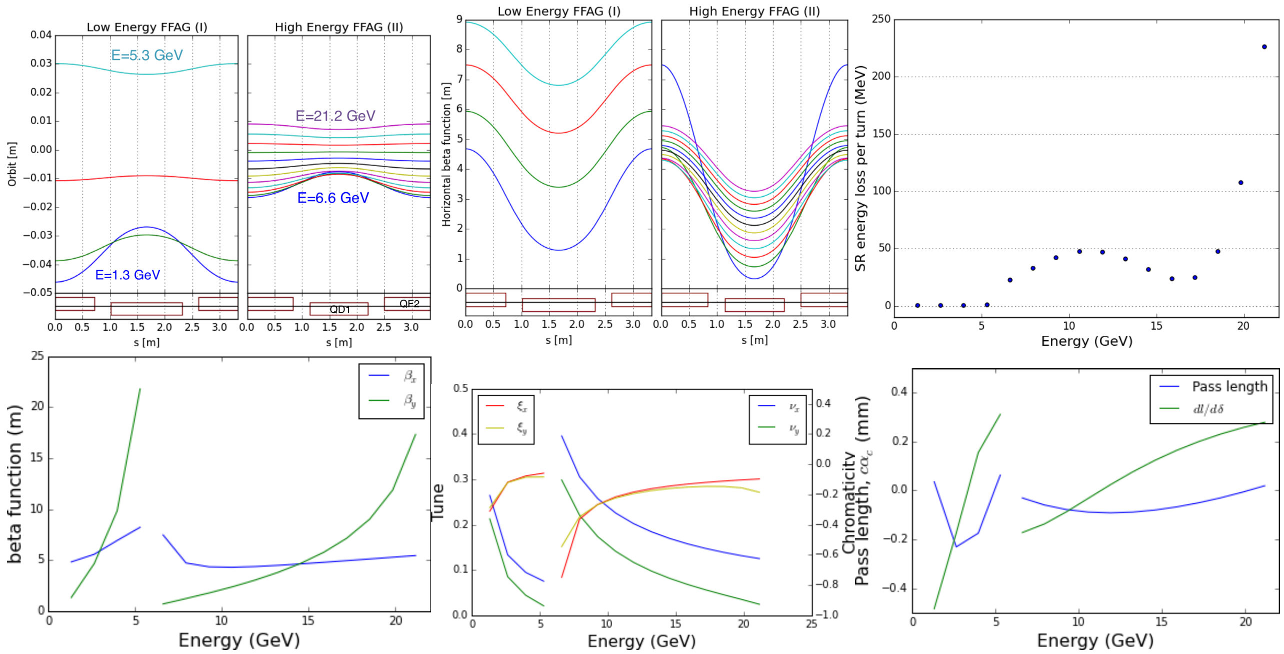

Figure 2: The orbit, optics, time of flight and radiation power of the optimized FFAG double cell.

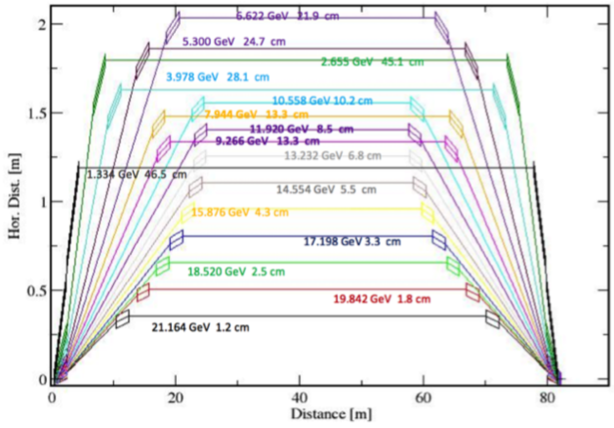

Figure 3: Layout of the splitter/combiner

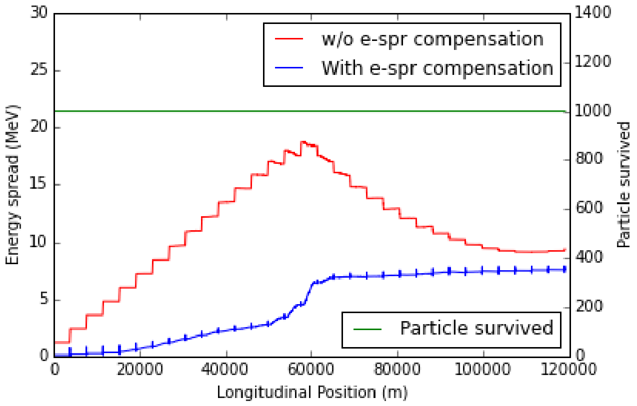

Figure 4: Comparison of the energy spread with (blue line) and without (redline) the energy spread compensator cavities . The green curve indicates the survived particle in the start-to-end tracking.

Using 6-D symplectic matrix to represent the unfinished beamlines, we established a 'skeleton version' of the start-to-end simulation frame for the eRHIC ERL. It includes the main linac with the options of including the energy loss compensating cavities (2^{nd} harmonic cavities) and the energy spread compensating cavities (5^{th} harmonic cavities), the 6-D symplectic matrices with constant vector for spreader and combiners for each energy and the two FFAG beam lines which consists of 720 FFAG cells. The constant vector in the spreader and combiner are used to provide proper transverse shift for the entrance of the FFAGs and the proper pass length adjustment to ensure the energy recovery process. In the simulation, the electron bunches starts at the injection energy of the ERL with accelerating phase, then pass through the linac, and the corresponding spreader/combiners and FFAGs. With correct length adjustments, the bunch will gain energy in multiple passes and reach the collision energy. With the extra half wavelength in the highest energy spreader/combiner, the bunch will be decelerated to the dump energy.

The first study on this skeleton model is the longitudinal dynamics study. We present one example which studies whether the energy spread compensation cavities can be removed. The main challenge of removing the cavity is the increased energy spread due to the RF curvature. The electron-ion collision does not pose a strong requirement on the energy spread at IP as long as the the spread won't cause noticeable chromatic emittance growth. However, the energy spread at the beam dump must be well controlled to prevent beam loss before the dump.

Figure 4 compares the electron beam accelerated to and decelerated from 21.2 GeV top energy, with (shown in the

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blue line) or without (shown in the red line) the energy spread compensating cavity. When no energy spread compensation is present, the energy spread is accumulating in the accelerating stage, mainly due to the RF curvature. In the decelerating stage, the energy spread cannot be fully compensated by the negative curvature due to the nonlinearity of the FFAG with respect to beam energy and synchrotron radiation. We have to optimize the R_{56} in the low energy spreader/combiners from its initial values to reach comparable energy spread at the beam dump, as the case with the energy spread compensation. Green lines indicates in both cases, no beam loss can be observed in the tracking.

BEAM-BEAM EFFECT IN ERL BASED EIC

Beam beam effects present one of the major restrictions in achieving the higher luminosities. The special 'linac-ring' scheme removes the beam-beam parameter limitation of the electron beam, hence higher luminosity can be achieved [6]. This also bring new challenges due to the beam-beam effect in the 'linac-ring' scheme, including the electron disruption effect, the electron pinch effect, the ion-beam kink instability and the ion beam heating due to the electron beam noise.

The electron disruption effect and the pinch effect rise due to the large beam-beam parameter of the electron beam. The strong nonlinear beam interaction field will distort the electron beam distribution and the large linear beam-beam tune shift leads to significant mismatch between the design optics and the electron beam distribution. Figure 5 shows the beam distribution after the collision and Figure 6 illustrates the electron beam size shrinking in the opposing ion beam (the pinch effect) and the electron beam rms emittance growth. The pinch effect in one hand will enhance the luminosity from 3.3×10^{33} cm^{-2}s^{-1} to 4.9×10^{33} cm^{-2}s^{-1}, a factor of 1.48. However, this effect also boosts the local beam-beam force to the opposing ions beam, which may affects the dynamics aperture of the ion beam.

To model the beam-beam force from the 'pinched electron bunch', it is not sufficient to model the transverse beam distribution as Gaussian and calculated the force using the second order moment of the beam distribution. The transverse distribution of the electron beam forms a dense core and a long tail due to to strong beam-beam force from the ion beam, as shown in Figure 5. Figure 7 compares the beam force calculated from the distribution and from the rms beam size. It indicates that a poisson solver is needed to precisely model the pinch effect on the ion beam.

For the ion beam, the largest challenge is the kink instability [7, 8], which arise due to the effective wake field of the beam-beam interaction with the electron beam. The electron beam is affected by the head of the ion beam and passes the imperfection of the head portion to its tail. The threshold of the instability can be estimated by the head-tail model as:

$$\xi_i d_e < 4\nu_s/\pi$$

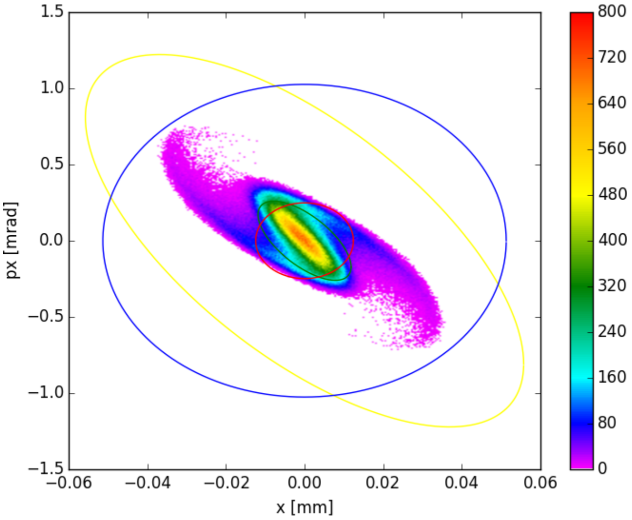

Figure 5: The electron beam distribution after the electron ion collision, with the parameter of the baseline eRHIC design.

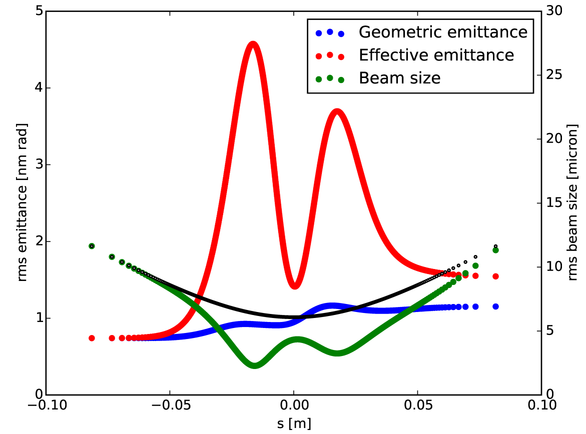

Figure 6: The electron beam distribution after the electron ion collision, with the parameter of the baseline eRHIC design.

The eRHIC parameter exceeds the threshold, therefore a fast deterioration of the ion beam quality is expected if no countermeasure is implemented. Simplified simulation study also predict that the instability will occur and can not be suppressed by the current chromaticity in RHIC [8]. A pickup-kicker type feedback system is studied in [9]. The inner-bunch modes of the instability can be picked up, amplified through a broad-band amplifier and corrected by the high band-width kicker. For the 5 cm eRHIC ion bunch length, the bandwidth of the feed-back system should be no narrower than 50-300 MHz.

Another important effect, which has not been studied, is the interplay of the space charge effect and the beam-beam effect. Both effects will cause complicate nonlinear resonance and reduce the beam life time. Previous beam experiments in RHIC shows that the beam with large space charge tune shift suffers short beam life time even with small beam-beam parameter. However, in electron-ion colliders, the beam-

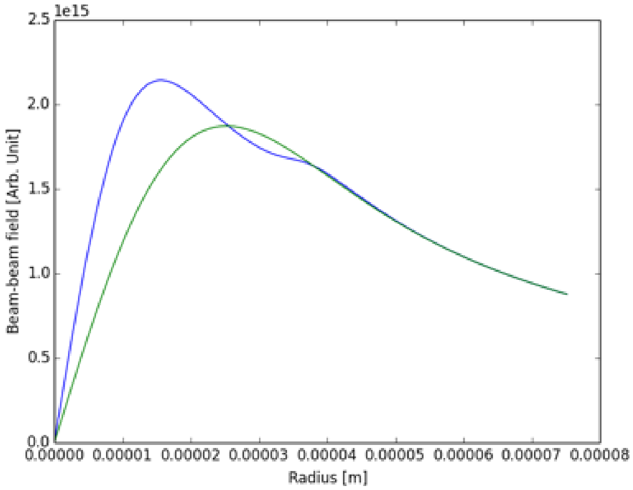

Figure 7: Comparison of the beam-beam force from a 'pinched' electron beam. The blue curve represents the force calculated from the beam distribution, while the green one is calculated from the rms beam size if the beam is assumed to have transverse Gaussian distribution.

beam parameter is the opposite sign as in the hadron/lepton colliders. A thorough simulation is required to study the interplay of the space charge effect and beam-beam effect from a pinched electron beam and find the maximum allowable space charge tune shift for the desire beam-beam parameter. The eRHIC luminosity is limited due to these effects, a recent method of space charge compensation [10] can be considered. However detail simulation of this method is required to ensure the beam stability.

COMPUTATION FOR COOLING CONCEPTS

To achieve the high luminosity, effective cooling methods for the ion beam are necessary. Coherent electron cooling (CEC) [11] is the promising method for high energy ion beam. It consists the modulator, FEL amplifier and kicker sections. Currently a proof-of-principle experiment is being prepared to prove the feasibility. A precise numerical model can not only guide the experiment, but also help to extrapolate the CEC proof-of-principle results to the cooling for eRHIC.

The delta-f PIC simulation [12, 13] is used to model the modulator and kicker section. In between, Genesis [14] can be use for the simulation of FEL amplifier. The simulation of the modulator with uniform transverse density shows very good agreement with the 1-D theory. However, a 3-D modulator model is still in an immature stage to simulate the finite beam sized effect as well as the presence of the focusing elements for the electron beam. To evaluate the cooling time precisely, we are also exploring the available 3-D self-consistent space charge libraries for the precise modulator and kicker modeling and benchmark with the delta-f PIC simulations.

SUMMARY

This article only highlighted several computation challenges of an ERL-ring scheme eRHIC. There are other essential requirements of beam dynamics studies such as the 3-D space charge modeling of the electron injector, the BBU simulation with harmonic cavities, the ion trapping effects.

The design of ERL-ring eRHIC is largely supported by the detailed simulation of the design, tracking and beam dynamics simulations. Through the numerical studies we already identified many challenges and found the corresponding countermeasures. More detailed numerical studies are demanded to further reduce the risks of the new concepts in the ERL-ring eRHIC design.

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