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eRHIC DESIGN UPDATE*

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Abstract

The future electron-ion collider (EIC) aims at an electron-proton luminosity of 10^{33} to 10^{34} cm^{-2}sec^{-1} and a center-of-mass energy range from 20 to 140 GeV. The eRHIC design has been continuously evolving over a couple of years and has reached a considerable level of maturity. The concept is generally conservative with very few risk items which are mitigated in various ways.

INTRODUCTION

The proposed electron-ion collider eRHIC will collide polarized electron and polarized light (proton, deuteron, or ^{3}He) or unpolarized heavy ion beams up to uranium at center-of-mass energies ranging from 20 to 140 GeV (electron-proton equivalent). The projected e-p luminosity of the facility reaches 10^{34} cm^{-2}sec^{-1}, thus meeting all the requirements laid out in the U.S. Nuclear Physics community's White Paper [1]. The machine design is based on the existing RHIC facility with its 3.8 km circumference tunnel and its hadron injector complex. The eRHIC hadron beam will be stored in the superconducting "Yellow" RHIC ring, while a new electron storage ring and a rapid cycling synchrotron [2] will be added in the same tunnel. Table 1 lists the main electron-proton parameters of eRHIC at a center-of-mass energy of 105 GeV, where the highest luminosity is reached.

INTERACTION REGION DESIGN

The eRHIC interaction region [3] is based on superconducting magnets to focus the beams at the interaction point, with vertical β-functions as low as a few centimeters. The peak magnetic fields of these quadrupoles, defined here as $B_{\text{peak}} = R \times g$, where R and g denote the aperture radius and the gradient, respectively, do not exceed 6 T. Therefore, all magnets can be built using NbTi superconductors. Furthermore, only a few magnets need to be built as collared magnets, while the majority can be manufactured using direct-wind technology.

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Table 1: eRHIC Electron-Proton Parameters at 105 GeV Center-of-Mass Energy

	proton	electron
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} hor./vert. [nm]	9.6/1.5	20.0/1.2
$\beta^*_{x,y}$ [cm]	90/4	43/5
b.-b. param. hor./vert.	0.014/0.007	0.073/0.100
σ_s [cm]	6	2
$\sigma_{\text{d}p/p}$ [10^{-4}]	6.8	5.8
τ_{IBS} long./transv. [h]	3.4/2.0	N/A
L [10^{33} cm^{-2}sec^{-1}]	10.05	

Separation of the two beams is accomplished by a 25 mrad crossing angle. A spectrometer dipole on the forward side of the ±4.5 m long central detector is equipped with detector components to increase the forward acceptance of the detector. The large aperture of this magnet is shared by both the eletron and the hadron beam. A bucking coil shields the electron beam from the magnetic field of the spectrometer. A dipole magnet on the forward side of the detector separates the hadron beam from the ±4 mrad forward neutron cone which is then detected in the zero degree calorimeter. The aperture of the electron quadrupoles on the rear side is large enough to accommodate the synchrotron radiation fan generated from a 12.5σ electron beam in the quadrupoles on the forward (incoming) side of the detector. Luminosity monitoring is based on detection of Bethe-Heitler photons generated in the interaction. Figure 1 shows a schematic view of the eRHIC interaction region.

ELECTRON STORAGE RING

The electron storage ring is based on FODO cells using conventional room-temperature magnets. The bending sections are realized as so-called super-bends, where each dipole is actually comprised of three individual magnets - two long dipoles with a short magnet in-between. The purpose of this arrangement is to generate additional synchrotron radiation damping and enhance the equilibrium emittance at energies

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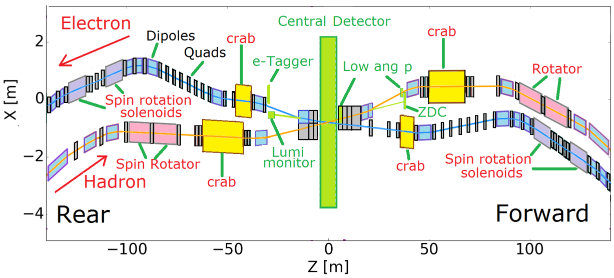

Figure 1: Schematic view of the eRHIC interaction region (top view). Note the different scales on the two axes.

below 10 GeV by powering the short, center dipole in reverse. At beam energies of 10 GeV and above all magnets are powered uniformly to minimize radiation losses.

The ends of the arcs adjacent to the interaction region are equipped with solenoid-based spin rotators. A solenoid rotates the spin from the vertical orientation in the arcs into the radial direction. A dipole then rotates the spins from the radial into the longitudinal orientation. This process is reversed after the interaction region. Separate sets of spin rotators are needed for the highest and lowest beam energies; at intermediate energies the solenoids are tuned such as to achieve the required net rotation. Additional optics constraints are met to achieve spin transparency of the entire straight section, including the spin rotators.

Using 36 sextupole families, a dynamic aperture of 20σ transverse and 12σ momentum acceptance has been achieved in the storage ring, with the vertical beam size based on a fully coupled machine. The effect of misalignments and field errors is currently under study. Preliminary results indicate that at 200 μm RMS magnet misalignment and 500 μrad RMS magnet roll error the effect on on-momentum dynamic aperture is not detectable.

HADRON STORAGE RING

The "Yellow" RHIC ring has to undergo a few modifications to be suitable as the eRHIC hadron ring. The heat induced in the stainless steel beam pipes due to the large number of bunches and high peak current would exceed the cryogenic limit of ≈ 0.5 W/m, and the 8.7 nsec bunch spacing would give rise to detrimental electron clouds. To overcome this, the beam pipes will be coated in-situ, first with a layer of copper to improve the surface conductivity, and then a layer or amorphous carbon to reduce the secondary electron yield. As a backup solution, the insertion of pre-coated sleeves is currently under consideration as well.

The injection system as well as the beam dump [4] will need to be upgraded to accommodate the shorter bunch spacing and higher beam intensity, respectively. The "inner" arc between IRs 12 and 2 will serve as a "shortcut" to allow synchronization of 41 GeV proton beams with the electron beam, while for energies between 100 and 275 GeV the "outer" arc of the "Yellow" ring will be used.

BEAM DYNAMICS

The beam-beam effect in eRHIC is very different for electrons and ions [5,6]. For electrons the beam-beam parameter is 0.1, as in the B-factories, and the bunch is short. Hence the electron crab cavities leave no significant non-linear residual and the dynamics are similar to those encountered in the B-factories. For ions the beam-beam parameter is 0.015, as in RHIC. The bunch is long, resulting in significant non-linear residuals from the crab cavities. Ongoing numerical studies indicate feasibility of the proposed crab-crossing scheme, but the beam-beam tune shifts are close to the allowed maximum.

Coherent instabilites in the storage rings are fairly generic. The electron storage ring requires $|Z/n| \leq 0.1\Omega$ which is standard and the beam-beam tune spread is a potent source of Landau damping. For the hadrons the existing RHIC appears to be adequate. Beam studies are planned to try and better constrain the narrow band longitudinal impedance. The ion instability in the electron storage ring [7, 8] limits the partial pressure of carbon monoxide to 0.24 nTorr for maximum luminosity.

POLARIZATION PERFORMANCE

eRHIC is designed to store beams with arbitrary spin patterns ("up" and "down") simultaneously. This requires a full energy polarized electron injector; a dedicated spin-transparent rapid-cycling synchrotron is being proposed as the most cost effective approach [2]. Since the Sokolov-Ternov effect will eventually result in all bunches being spin-polarized anti-parallel to the main dipole field, bunches polarized parallel to the dipole field need to be replaced at a rate much faster than the Sokolov-Ternov time constant which, at 18 GeV, is as short as 30 min.

Depolarization due to spin diffusion needs to be minimized as well. This requires spin matching of the interaction region straight section with its spin rotators. Simulations using the SITROS code [9] yield an equlibrium polarization of 50 percent in the electron storage ring. Assuming an injected polarization of 80 percent, and replacement times of 2 minutes for bunches with spins parallel to the main dipole field, 4 minutes for bunches with spin anti-parallel to the dipole field, results in an average polarization of 70 percent.

RHIC has reached proton polarization levels exceeding 60 percent at 275 GeV. Increasing the number of Siberian snakes in the "Yellow" ring from the present two to six will, in conjunction with incremental upgrades in the AGS, raise the proton polarization level to 80 percent in the eRHIC hadron ring. Furthermore, the increased number of Siberian snakes will enable acceleration and storage of polarized deuteron and ^{3}He beams as well.

ALTERNATIVE TO STRONG HADRON COOLING

Reaching luminosities as high as 10^{34} cm^{-2}sec^{-1} requires hadron beam parameters that result in intrabeam scattering

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growth times as short as 2 h. Without additional measures, the meaningful store duration would therefore be of the same order due to the associated luminosity degradation. Together with a typical turnaround time between stores of about 30 min, the average luminosity would be at least a factor of two lower than the peak luminosity.

The preferred countermeasure to prevent fast luminosity decay would be some form of strong electron cooling at store energy. However, the highest proton beam energy at which this technique was successfully applied was at 8 GeV in the FNAL Recycler Ring, using a DC electron beam generated and accelerated by a Pelletron. The electron beam energies required to cool at the much higher beam energies in the EIC hadron ring are far beyond what can be achieved by a DC accelerator. Instead, bunched electron beams accelerated in RF structures need to be employed. First signs of bunched beam electron cooling have recently been observed, albeit at lower energy [10].

An alternative scheme based on frequent replacement of the entire hadron ring fill at collision energy is under consideration. In this scheme, the existing "Blue" RHIC ring would serve as an on-energy injector to the "Yellow" collider ring. The "Blue" ring would be filled using the AGS, and an electron cooler at or slightly above injection energy would be employed to achieve the desired small vertical emittance. The "Blue" ring would then ramp up to the same energy as the "Yellow" ring, and the entire "Blue" fill would be transferred to the "Yellow" ring while simultaneously dumping the spent "Yellow" beam. This instantaneous beam replacement scheme minimizes the downtime between stores to the time it takes to cycle the detector voltage, thus keeping the luminosity within 90 percent of the peak value.

LUMINOSITY OPTIMIZATION AT LOW ENERGY

The luminosity and interaction region design described in previous sections was optimized around a center-of-mass energy of 100 GeV in order to maximize the discovery potential of the machine. However, the eRHIC design allows for a different choice of the optimization, aiming at maximizing the luminosity at a lower center-of-mass energy.

Lower beam energies allow for a number of interaction region design modifications that result in higher luminosity at those lower energies:

- Low electron beam energies ($E_e \leq 10$ GeV) allow installation of the low-β quadrupoles closer to the IP due to the larger scattering angles corresponding to $Q^2 \simeq 1\,\text{GeV}^2$;
- The increased crossing angle required to ensure sufficient separation of the two beams at the low-β quadrupoles is more easily compensated by crab crossing due to the lower beam energy;
- The reduced electron beam energy eases managing the synchrotron radiation fan generated by the electron beam in the low-β quadrupoles.

Table 2: Comparison of Parameters for High and Low Center-of-Mass Energy Luminosity Optimization

	Low CM Energy	High CM Energy
CM energy [GeV]	63	105
Crossing angle [mrad]	50	25
Max. β-function [m]	2700	1800
τ_{IBS} long./transv. [h]	0.4/0.4	3.4/2.0
Luminosity [10^{33} cm^{-2}sec^{-1}]	12.4	10.0

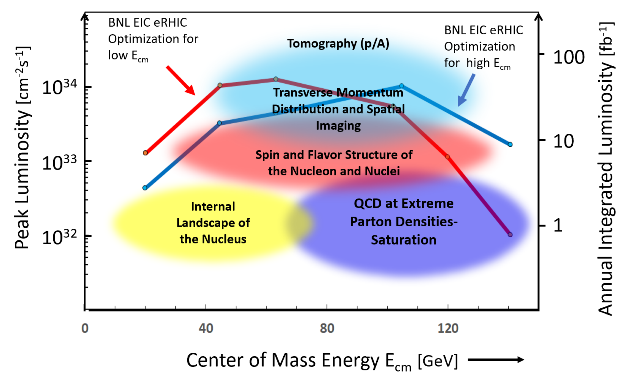

Figure 2: Luminosity vs. center-of-mass energy for two different optimizations of the interaction region and beam parameters. The blue curve, which shows an optimization at 105 GeV CM energy, is based on 1160 bunches and 25 mrad crossing angle, while the red curve, optimized at 63 GeV, is based on 2320 bunches and 50 mrad crossing angle.

A key ingredient to maximizing the luminosity at lower energies is a larger number of bunches, while keeping the total beam currents constant. The lower bunch intensities keep the beam-beam and space charge parameters within established limits. The increased IBS growth rates are more easily compensated by electron cooling due to the lower hadron beam energy as well. Table 2 shows a comparison of the main parameters for low and high center-of-mass energy luminosity optimization. The corresponding luminosity curves over the entire center-of-mass energy range are depicted in Fig. 2.

POTENTIAL FUTURE ENERGY UPGRADE

While the eRHIC design covers the entire center-of-mass energy range required by the White Paper [1] from Day One, discoveries made during operations may warrant an upgrade to higher energies. With the present hadron ring magnets operating at maximum magnetic fields of approximately 4 T, doubling the hadron beam energy can be accomplished by replacing these with 8 T magnets, which would be the same strength as in the LHC.

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