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eRHIC DESIGN OVERVIEW*

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Abstract

The Electron-Ion Collider (EIC) is being envisioned as the next facility to be constructed by the DOE Nuclear Physics program. Brookhaven National Laboratory is proposing eRHIC, a facility based on the existing RHIC complex as a cost effective realization of the EIC project with a peak luminosity of 10^{34} cm^{-2}sec^{-1}. An electron storage ring with an energy range from 5 to 18 GeV will be added in the existing RHIC tunnel. A spin-transparent rapid-cycling synchrotron (RCS) will serve as a full-energy polarized electron injector. Recent design improvements include reduction of the IR magnet strengths to avoid the necessity for Nb_3Sn magnets, and a novel hadron injection scheme to maximize the integrated luminosity. We will provide an overview of this proposed project and present the current design status.

INTRODUCTION

In its White Paper, the U.S. Nuclear Physics community set forth the requirements for a future electron-ion collider (EIC) as follows:

- An electron-proton center-of-mass energy of 20 to 140 GeV;
- An electron-proton luminosity of 10^{33} to 10^{34} cm^{-2}sec^{-1};
- Spin polarized electron and light ion (proton, deuteron, ^{3}He) beams, with polarization levels of at least 70 percent;
- Arbitrary spin patterns in both beams;
- A wide range of ion species from protons to uranium.

Brookhaven National Laboratory is proposing eRHIC, an electron-ion collider based on the existing RHIC facility. RHIC consists of two superconducting storage rings (“Blue” and “Yellow”) with a circumference of 3.8 km that intersect at six equidistantly spaced locations around the ring. This facility is ideally suited as a base for the EIC for a number of reasons:

- The hadron beam parameters of RHIC, which has exceeded its design luminosity 44-fold, are very close to the parameters required for eRHIC;
- Ion species from protons to uranium have been routinely accelerated, stored, and collided;
- Proton polarization levels of 60 percent have been routinely achieved at 255 GeV beam energy, and with additional Siberian snakes are expected to reach 70%;
- The large 3.8 km circumference and a maximum proton beam energy of 275 GeV allow for an electron-proton center-of-mass energy of 140 GeV with an 18 GeV electron storage ring installed in the same tunnel, assuming a straightforward proton energy upgrade from 255 to 275 GeV.

Table 1: eRHIC Electron-proton Machine Parameters at 105 GeV Center-of-mass Energy [1]. Electron-ion Parameters are Given in [2]

species	proton	electron
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
ϵ_{RMS} hor./vert. [nm]	9.2/1.6	20.0/1.3
$\beta^*_{x,y}$ [cm]	90/4.0	41/5.0
b.-b. param. hor./vert.	0.014/0.007	0.072/0.100
σ_s [cm]	6.0	1.9
$\sigma_{\mathrm{d}p/p}$ [10^{-4}]	7.0	5.5
τ_{IBS} long./transv. [h]	4/2	N/A
L [10^{33} cm^{-2}sec^{-1}]	10.5	

The eRHIC concept consists of combining the existing “Yellow” RHIC ring with a 5 to 18 GeV electron storage ring plus a full energy injector synchrotron installed in the existing RHIC tunnel. Electron-ion collisions are provided in up to two interaction regions which are equipped with detectors. Figure 1 shows a schematic overview of the entire eRHIC facility, including the existing hadron complex. Table 1 lists the eRHIC machine parameters at a center-of-mass energy of 105 GeV where the highest luminosity of 1.05×10^{34} cm^{-2}sec^{-1} is attained.

ELECTRON STORAGE RING

The six arcs of the electron storage ring are comprised of approximately 16 m long FODO cells [3]. The bending sections in these cells are realized as super-bends with each section consisting of three individual dipoles, namely two

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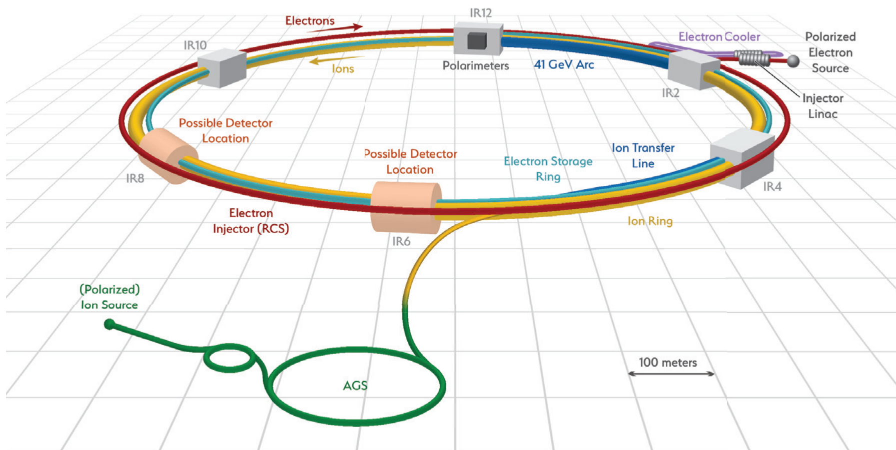

Figure 1: Schematic view of the electron-ion collider eRHIC

2.66 m long dipoles with a 0.45 m long dipole in-between. At beam energies of 10 GeV and above all three segments are powered uniformly for a smooth, uniform bend, while at 5 GeV the polarity of the short center dipole is reversed, resulting in additional synchrotron radiation in this configuration to provide the required fast radiation damping allowing for the high beam-beam parameter of 0.1.

Luminosity optimization over the entire eRHIC energy range requires electron beam emittances of 20 to 22 nm at all energies from 5 to 18 GeV. This is achieved by operating the storage ring with a FODO cell phase advance of 90 degrees at 18 GeV, and 60 degrees at 5 and 10 GeV, in conjunction with the super-bends at 5 GeV.

Arbitrary spin patterns, with bunches with spin "up" and bunches with spin "down" in the arcs simultaneously stored, are achieved by injecting bunches with the desired spin orientation from a full-energy polarized injector. To provide longitudinally spin-polarized electrons at each interaction point (IP), sets of solenoid-based spin rotators are installed on either side of each IP. To counteract the Sokolov-Ternov effect and spin diffusion in the ring, individual bunches are continuously replaced at a rate of about one bunch per second.

RAPID CYCLING SYNCHROTRON

A rapid cycling synchrotron (RCS) serves as full energy polarized injector for the electrons [4]. Spin transparency is achieved by a high super-periodicity of $P = 96$, and an integer tune of $[Q_y] = 50$. This choice avoids intrinsic spin resonances over the entire energy range from 400 MeV to 18 GeV, which are described by the resonance condition

$$G \cdot \gamma = n \cdot P \pm [Q_y], \tag{1}$$

where n is an integer and $G = 1.15965 \times 10^{-3}$ is the anomalous gyromagnetic ratio of the electron, while γ is the relativistic Lorentz factor.

HADRON STORAGE RING

The "Yellow" RHIC ring will serve as the hadron ring for eRHIC, requiring a few modifications. The increased number of bunches (from 109 to 1160) and higher peak current would lead to unacceptable heating of the stainless steel vacuum pipes in the superconducting magnets. To improve the conductivity of the beam pipe, in-situ copper coating will be applied [5, 6]. A layer of amorphous carbon will also be added to reduce the secondary electron yield in order to avoid electron cloud instabilities.

The increased number of bunches necessitates faster injection kickers due to the reduced bunch spacing. Since the total length of this new kicker section exceeds the space available in the present location, the AGS-to-RHIC (AtR) transfer line will be extended from the present location in IR6 to the new kicker location in IR4, where there is plenty of warm space available. This extension will utilize the "Blue" arc between IRs 6 and 4 [7].

The large center-of-mass energy range requires operating at a range of ion energies. Due to the relatively low ion energy the ion velocity at different energies varies substantially. In order to maintain synchronization between the electron and hadron beams, the circumference of one of the two rings has to be adjusted. This is accomplished by an RF frequency change for energies between 100 and 275 GeV, with 133 GeV corresponding to the nominal design orbit in the center of the beam pipe. To operate at lower energies, the inner "Blue" arc instead of the outer "Yellow" arc will be used in the sextant between IRs 12 and 2. With the radius of inner and outer arcs differing by about 90 cm, this corresponds to a circumference change of about 90 cm. This circumference is suitable for operating at a proton beam energy of 41 GeV.

BEAM-BEAM DYNAMICS

The 25 mrad crossing angle requires crab cavities [8] to restore the luminosity reduction associated with the crossing, and to minimize hadron beam emittance growth. Simulation

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studies have been performed to determine the required crab cavity frequency and the possible need of higher harmonic cavities to linearize the kick along the hadron bunches. In order to limit the transverse emittance growth to less than five percent per hour, a combination of either 200 and 400 MHz or 400, 800, 1200, and 1600 MHz crab cavities is required according to these studies.

ELECTRON COOLING

The usable store length in the collider is limited by the intrabeam scattering (IBS) growth time of approximately 2 hours. Since the turnaround time between stores is of the order of 30 minutes, the average luminosity would be only about half the peak value. To counteract the fast emittance growth due to IBS, and therefore increase the usable store length, strong hadron cooling is required. Several cooling schemes are currently under consideration, like "conventional" cooling with a bunched electron beam, or variations of coherent electron cooling where an electron beam is used as a pickup and kicker in a very high bandwidth stochastic cooling scheme. Among these latter concepts, coherent electron cooling with a micro-bunched 100 mA electron beam appears most promising in simulations.

A more conventional cooling design involves an electron storage ring. The design is quite preliminary but bunch charges ~ 15 nC are planned. The stored electron bunch is subject to intrabeam scattering and heating by the ion bunch. The resulting momentum spread is $\sigma_p \sim 0.001$ and the transverse emittance is around 7 nm. Cooling times of order an hour for 275 GeV protons look feasible.

MITIGATION OF ELECTRON COOLING RISK

Electron cooling has never been demonstrated above proton energies of 8 GeV, which was achieved at the FNAL Recycler ring using a DC electron beam provided by a pelletron. Electron cooling with a bunched electron beam, as would be required for eRHIC due to the high hadron beam energy, has only very recently been achieved, albeit at only a few GeV hadron beam energy [9]. Due to the strong energy dependence of the cooling force, much higher electron beam currents would be required for eRHIC. Coherent electron cooling has not yet been demonstrated experimentally.

An alternative scheme is being considered that utilizes the "Blue" RHIC ring as a full energy injector. The entire fill in the "Yellow" storage ring is replaced at store energy every 15 minutes. With the 2 h IBS growth time being much longer, the luminosity is therefore kept almost constant. The required beam emittances would be achieved by cooling at or slightly above injection energy in the "Blue" ring, which is much easier than cooling at store energies. This scheme requires a challenging injection kicker in the "Yellow" storage ring with rise and fall times of about one microsecond, and a flattop of 12 μsec (one turn) with very little ripple. To minimize the turnaround time the detector would either have to stay on during the refill process, or be designed such that it can be turned off and back on in less than a minute or so.

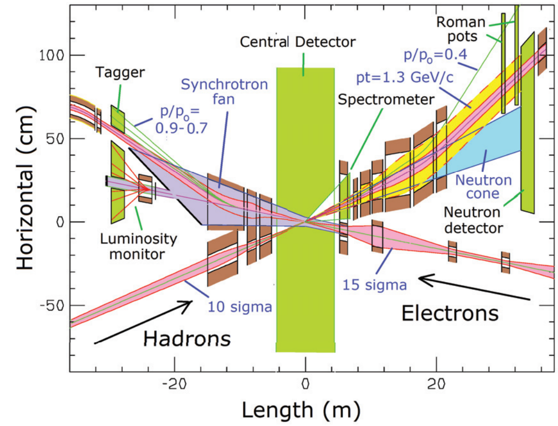

Figure 2: Schematic view of the eRHIC IR (top view). Note the different scales on the two axes

INTERACTION REGION DESIGN

The eRHIC interaction region (IR) shown in Figure 2 serves multiple purposes [10]:

• Focus both electron and hadron beams to small spot sizes at the interaction point (IP), with β-functions down to a few centimeters;

• Separate the two beams by means of a 25 mrad crossing angle;

• Separate the hadron beam from the 5 mrad forward neutron cone;

• Separate the electron beam from the Bethe-Heitler photons used for luminosity measurements;

• Safely pass the synchrotron radiation fan generated upstream of the IP through the detector.

COLLECTIVE EFFECTS

The broad band impedance of the ring has been scaled from NSLS-II [11] and is well modeled by a resistive wall wakefield with a resistivity of $\rho = 7\ \mu\Omega$/cm and a round pipe of radius 2 cm. The broad band transverse impedance is modeled as the same resistive wall impedance. The resistive wall impedance at the betatron sidebands for the actual ring gives a maximum transverse resistance of 12 MΩ/m. The narrow band longitudinal resistance is dominated by RF cavities. The most dangerous mode has a resonant frequency of 1.1 GHz with a quality factor of 70 and a net shunt impedance for 13 cavities of 24 kΩ. For nominal currents at 10 GeV the transverse modes are damped by the beam-beam force. The narrow band longitudinal impedance leads to instabilities. A damper corresponding to $\Im(Q_s) = 0.001$ is plenty to damp these instabilities.

Carbon monoxide can lead to a multi-bunch ion instability. The beam-beam tune spread is very effective in damping these but the average pressure of CO needs to be less than 1×10^{-7} Pa at 10 GeV and about half that at 5 GeV.

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