POTENTIAL USE OF eRHIC's ERL FOR FELS AND LIGHT SOURCES

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Abstract

One of the designs of a future electron-hadron collider, eRHIC, is based on a 5-10 GeV high current energy-recovery linac (ERL) with possible extension of its energy to 20 GeV. This ERL will operate with high brightness electron beams, which naturally match requirements for X-ray FELs and other next generation light sources. In this paper we discuss possible scenarios of using the eRHIC ERL in parasitic and dedicated mode for SASE, HGHG and oscillator X-ray FELs.

INTRODUCTION

A Twenty-Year Outlook DoE document on "Facilities for the Future Science" [1] includes a new electron-hadron collider at BNL, based on the Relativistic Heavy Ion Collider (RHIC) and a new electron accelerator.

Table 1. Main parameters of eRHIC

RHIC	
Ring circumference [m]	3834
Protons: number of bunches	360
Beam energy [GeV]	26 - 250
Protons per bunch (max)	$2.0 \cdot 10^{11}$
Normalized 96% emittance [μm]	14.5
Gold ions: number of bunches	360
Beam energy [GeV/u]	50 - 100
Ions per bunch (max)	$2.0 \cdot 109$
Normalized 96% emittance [μm]	6
Electrons: Beam rep-rate [MHz]	28.15
Beam energy [GeV]	5 – 20
γ, Relativistic factor	$1 - 4\ 10^4$
RMS normalized emittance [μm]	5- 50
Beam emittance @ 20 GeV [Å]	1.25-12.5
RMS Bunch length [psec]	30
Charge per bunch [nC]	1.6 -16
Average e-beam current [A]	0.45

The main goal of the eRHIC is to explore the physics at so-called "low-x", and the physics of color-glass condensate in electron-hadron collisions [2]. In response, the Collider-Accelerator Department at BNL in collaboration with Bates Laboratory at MIT issues the eRHIC ZDR (0^{th}–order design report), which includes a linac-ring eRHIC design based on 10 GeV ERL [3]. The design is based on CW linac with high current super-conducting RF (SRF) 5-cell cavities, which are under construction at BNL [4,5] and a polarized photo-injector using a dedicated 2 kW circularly polarized FEL [3]. The main parameters of the eRHIC are summarized in Table 1. The parameters of the electron beam are very impressive and it can easily be used as a next generation light source in parasitic mode.

In addition, RHIC rings operate only for about 30 weeks per year, which leaves about 4 and a half months for dedicated mode of ERL operation as a light source. In this case we suggest using a lower charge per bunch and a higher rep-rate, while keeping the same level of average e-beam current (~ 500 mA). The e-beam parameters for this mode of operation are listed in Table 2.

Table 2. Main parameters in dedicated mode

Electrons	
Beam rep-rate [MHz]	703.75
Beam energy [GeV]	5 – 20
γ, Relativistic factor	$1 - 4\ 10^4$
RMS normalized emittance [μm]	0.9
Beam emittance @ 20 GeV [Å]	0.18
Full transverse coherence λ[Å]	1.13
photon energy [keV]	11
RMS Bunch length [psec]	0.03 - 3
Charge per bunch [nC]	0.7
Average e-beam current [A]	0.5

Parameters of the electron beam in eRHIC's ERL naturally match the requirements for a next generation light source. First, let us note that the eRHIC ERL light source would have transverse coherence in the X-ray range up to 11 keV. Second, 20 GeV operation of the ERL will extend the range of spontaneous radiation from undulators and bending magnets into γ-ray range and open new possibilities for low energy nuclear physics. Third, the ERL is a perfect driver for high power (i.e. kilowatts of CW power) FELs ranging from hard X-rays to VUV. Fourth, it is also a perfect match for generating beam of very intense circularly polarized γ-rays with energies up to 12 GeV.

In this paper, we take a first look at the potential of the ERL at eRHIC as a light source. We describe two possible layouts, discuss the effects of synchrotron radiation in the ERL's arcs on the e-beam parameters and, finally, present a straw-man design of X-ray FELs based on SASE, distributed optical klystron (DOK) and optics-free oscillator schemes.

LAYOUTS OF THE ERL-based eRHIC

Fig.1 shows a possible layout for a stand-along ERL. The electron beam, generated in SRF photo-injector is accelerated to an energy of 0.5 GeV by low energy ERL, followed by two passes through high energy linacs. This layout provides for a natural use of the beam-lines installed on the 2.5, 5, 7.5 and 10 GeV arcs for a variety of sources of spontaneous radiation. After passing through the collision point, the beam is going through the energy recovery process, which doubles the beam current in each arc (except that at 10 GeV). FEL can be installed in a straight section connecting the end of the 10-GeV arc with the linac. This scheme is limited to maximum energy of ~ 10 GeV by the size of the accelerator and the acceptable power of the synchrotron radiation.

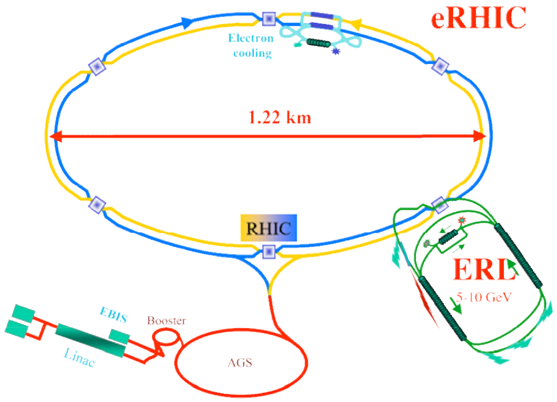

Fig. 1 Layout of eRHIC with a stand-along 10 GeV ERL.

Fig.2 shows a more attractive layout of ERL sharing a 3.8 km tunnel with two hadron storage rings (called the blue and the yellow).

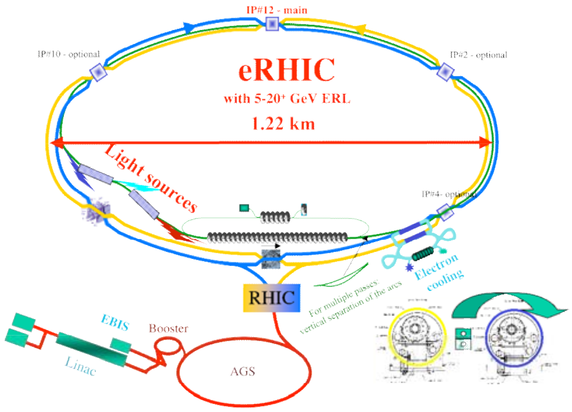

Fig. 2 Layout of the eRHIC ERL in the RHIC tunnel.

This layout provides for multiple collision points for eRHIC and also allows an increase in the energy of electron beam to 20 GeV or above while keeping power of synchrotron radiation under control (and especially keeping linear power density well below 1 kW/m). Obviously, this layout has many advantages for the light source applications. It has best emittance and hundreds of meters of free space for hard X-ray FELs.

Similarly to other ERLs, the electron beam is generated in the gun, pre-accelerated in the low energy SRF linac, then injected into the main high energy SRF linac, which it passes twice to reach maximum energy of 20 GeV. Then the beam is decelerated to recover its energy back into RF field and is finally dumped.

On the way to the final energy the electron beam passes through the arcs, where synchrotron radiation may significantly affect the e-beam parameters. Our present design is based on 150 25-meter long achromatic cells (see sketch in Fig. 3) with a bending radius of 400 m in the dipoles. The energy loss for synchrotron radiation is 35 MeV for 20 GeV electrons.

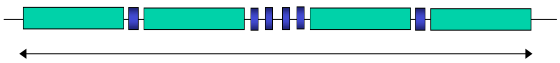

Fig. 3 A sketch of 25 meter-long achromatic cell for 10 and 20 GeV arcs in the eRHIC's ERL.

Table 3. Parameters of the 10 GeV e-beam

Energy	10	GeV	
Radius, average	610.20	m	
B, magnets	0.83	kGs	
ε_{norm}	9.50E-07	m rad	
ε	0.485	Å	
Bunchlength	from 0.1 to 2	psec	
$\Delta\varepsilon$	0.001	Å	0.10%
ε , final	0.486	Å	
RMS energy spread	4.49E-06		

Table 4. Parameters of the 10 GeV e-beam

Energy	20	GeV	
Radius, average	610.20	m	
B, magnets	1.67	kGs	
ε_{norm}	9.50E-07	m rad	
ε	0.243	Å rad	
Bunch length	from 0.1 to 2	psec	
$\Delta\varepsilon$	0.016	Å rad	6.70%
ε , final	0.259	Å rad	
RMS energy spread	2.54E-05		

The beam parameters at the end of the arc for 10 GeV and 20 GeV beams and some basic parameters of the arcs are given in Table 3 and Table 4, correspondently. In this design, synchrotron radiation determines the energy spread of both 10 GeV and 20 GeV, while contribution of the initial energy spread is negligible. In contrast, this low emittance lattice of the arc provides for essential preservation of the initial normalized transverse emittance: the horizontal emittance grows by 0.1% for 10 GeV beam and by 6.7% for 20 GeV beam. Extremely high quality of the electron beam in eRHIC's ERL provides for a natural use of its strong spontaneous radiation from its regular or *specialized* magnets (see Table below).

Table 5. Synchrotron radiation at 20 GeV.

Loss per turn	35.40	MeV
Power	17.70	MW
λ_c (regular bend)	0.28	Å
E_c (regular bend)	44.35	KeV
λ_c (10 T bend)	*0.0047*	*Å*
E_c (10 T bend)	*2661*	*KeV*

Energy of 20 GeV makes building hard X-ray sources an easy task: a wiggler with period of 2 cm will generate fundamental wavelength of ~ 0.1 Å. The range of expected spectral brightness for these sources of spontaneous radiation is shown n Fig. 5.

ERL-based FELs

Low emittance, high peak current of the 20 GeV ERL operating in dedicated mode (Table 2) make it an attractive driver for high gain X-ray FELs, which can operate in SASE [6], and HGHG [7] modes. The very low energy spread of this source makes it attractive to use a scheme of distributed optical klystron (DOK) [8], schematically shown in Fig. 4. DOK driven by a low energy spread beam has shorter gain length (***$L_{G\ DOK}$***) compared with that of a SASE FEL (***L_G***):

$$L_{G\ DOK} \cong L_G \cdot \left\{ e^{\frac{1}{4}} \cdot \sqrt[2]{\frac{4\pi L_G}{\lambda_w}\frac{\sigma_\gamma}{\gamma}} / \kappa^{3/2} \right\}; \ \kappa = \frac{L_w}{L_c}.$$

where σ_γ / γ is RMS energy spread of electron beam and λ_w is the wiggler period. DOK reduces the gain length X-ray FELs at eRHIC 2.2 and 5 fold at energies of 20 GeV and 10 GeV, correspondingly. Table 6 summarizes the parameters of ERL based FELs at eRHIC.

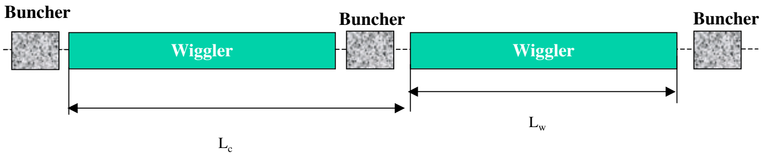

Fig. 4 A sketch of distributed optical klystron, which consists of repeating cells comprising a wiggler and a buncher. Similar to the traditional optical klystron [1], the slippage in the buncher is significantly larger that in the wiggler. This additional bunching combined with low energy spread beam enhances the FEL gain.

Table 6. Main parameters of X-ray FEL driven by ERL at eRHIC

Energy, GeV	20	20	15	15	10	10
Wavelength, Å	0.5	1	0.87	1.8	2	4
Bunch length, psec	0.2	0.2	0.27	0.27	0.4	0.4
Peak Current, kA	5	5	3.75	3.75	2.5	2.5
Wiggler period, cm	2.5	3	2.5	3	2.5	3
SASE gain length, m	**7.5**	**4.3**	**5.5**	**3.3**	**3.7**	**2.4**
SASE Saturation length, m	100	60	76	47	51	34
Saturation power, GW	7.7	19	6.4	14	4.5	9
DOK, gain length, m	**3.5**	**1.4**	**1.5**	**0.65**	**0.51**	**0.25**
DOK, saturation length, m	47	19	21	9	7	3.5

A simple use of SASE FEL combined with a very high repetition rate of ERL at eRHIC leads to extremely high average lasing power from 0.6 MW to 1.3 MW at wavelength of 1Å (photon energy 12 keV). The solution for this potential problem is either to use Fourier limited source. i.e. either HGHG FEL or optics-free FEL oscillator (OFFO) [10], the schematic of which is sketched in Fig. 6 The main ERL drives an high gain FEL amplifier with gain of ~ 10^5. Amplified light passes through a micro-wiggler with low energy, low current, low emittance e-beam used for feed-back. The feed-back-beam carries-on the modulation to the entrance of the FEL, where it radiates coherently in another micro-wiggler. This radiation is then amplified by the new electron bunch in the high energy FEL. This process closes the loop and makes this FEL an oscillator [12].

The advantage of this scheme is that this FEL is fully tunable, optics independent and has a line-width of an oscillator. This scheme would allow reducing the line-width of X-ray FEL to a *few parts per million* compared with a few parts per thousands, typical for

SASE FELs [11]. In this case, the average power of X-ray FEL at eRHIC with average spectral brightness in 10^{30} range (see Fig.5) will reduce to manageable levels of tens of hundreds of watts.

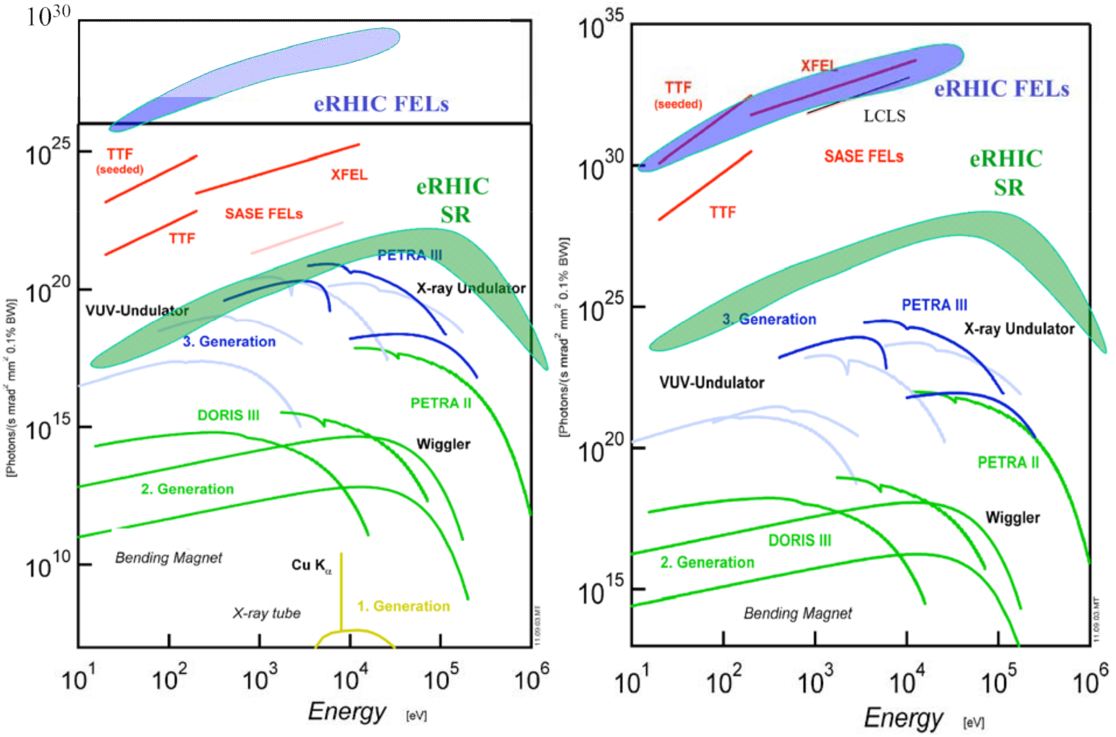

Fig.5 Average and peak spectral brightness of eRHIC light source (blue – FELs, green – spontaneous radiation) compared with other sources. While being similar to SASE FEL sources in peak spectral brightness, the average spectral brightness of eRHIC FELs would exceed the rest of the light sources (existing and proposed) by about 5 orders of magnitude.

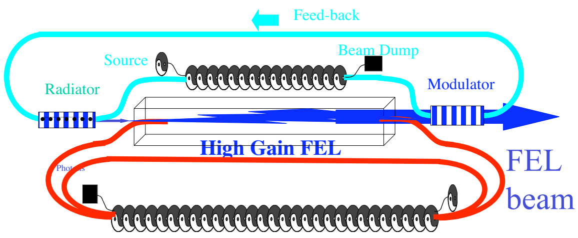

Fig. 6 Schematic of OFFO using two ERLs.

CONCLUSION

Future high current 10-20 GeV ERL for eRHIC electron-hadron collider has outstanding potential to become a next generation light source with unprecedented levels of average spectral brightness.

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