BNL-94067-2010-CP

FEL potential of eRHIC

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Presented at the 32nd Free Electron Laser Conference
Malmo City, Sweden
August 23-27, 2010

DISCLAIMER

FEL POTENTIAL OF eRHIC*

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Abstract

Brookhaven National Laboratory plans to build a 5-to-30 GeV energy-recovery linac (ERL) for its future electron-ion collider, eRHIC. In past few months, the Laboratory turned its attention to the potential of this unique machine for free electron lasers (FELS), which we initially assessed earlier [1]. In this paper, we present our current vision of a possible FEL farm, and of narrow-band FEL-oscillators driven by this accelerator.

INTRODUCTION

eRHIC, the proposed electron-ion collider at BNL, takes advantage of the existing Relativistic Heavy Ion Collider (RHIC) complex. Plans [2] call for adding a six-pass super-conducting (SRF) ERL to this complex to collide polarized- and unpolarized- electron beams with heavy ions (with energies up to 130 GeV per nucleon) and with polarized protons (with energies up to 325 GeV). RHIC, with a circumference of 3.834 km, has three-fold symmetry and six straight sections each ~ 250 m long. Two of these straight sections will accommodate 703-MHz SRF linacs. The maximum energy of the electron beam in eRHIC will be reached in stages, from 5 GeV to 30 GeV, by increasing the lengths of its SRF linacs. We plan to install at the start the six-pass magnetic system with small gap magnets. The structure of the eRHIC's electron beam will be identical with that of its hadron beam, viz., 166 bunches will be filled, reserving about a one-microsecond gap for the abort kicker.

With modest modifications, we can assure that eRHIC's ERL will become an excellent driver for continuous wave (CW) FELs (see Fig.1). The eRHIC's beam structure will support the operation of several such FELs in parasitic mode.

We could put from a few to a few hundred FEL electron bunches within the one-microsecond gap not used in the eRHIC collisions. Some bunches might be extracted (with a natural limitation on the total beam power) and used in a single-pass FEL without energy recovery. Another possibility being discussed is having an X-ray optics-free-FEL-oscillator (OFFELO) [3,4]. Dedicated operation would be available when the eRHIC is not operating.

Fig.1 shows that we can use beams at various energies from 2.5- to 30-GeV for FEL operations. Naturally, the 5-15 GeV range will be of most interest for generating X-ray beams with extremely high average brightness. Such sources can be important for the next generation of user applications. X-rays are excellent momentum- and energy- resolved probes that couple to all condensed-matter excitations. There is a very strong, diverse scientific case making inelastic x-ray scattering a uniquely powerful tool therein. The only limitation stopping scientists from using this tool is the absence of appropriate sources delivering the required flux of monochromatic X-ray photons, i.e., with an average spectral brightness in the range of 10^{26} – 10^{29} ph/sec/mm^2/mrad^2/0.1%BW. . All existing and planned X-ray FELs fall short of this target.

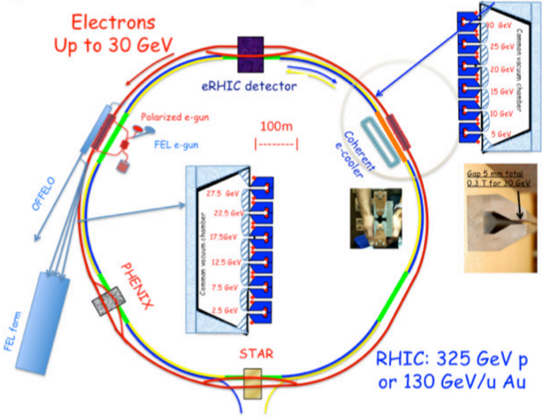

Figure 1: Layout of the eRHIC facility illustrating the potential of adding of FEL beam-lines. eRHIC is an ERL-based proposed future polarized electron-ion collider at RHIC. Incorporating a dedicated gun for FEL operation will assure that this facility can be used for high rep-rate CW FELs.

As illustrated in Fig.2, an meV resolution is needed for inelastic-scattering experiments. The best modern light sources (i.e., third-generation ones [4] and X-ray FELs [5]) yield an X-ray flux of about 10^9 – 10^{10} photons/s/meV. The resulting rate of inelastic scattering in high- temperature superconductors (HiTc), at a few counts per hour, practically is unobservable. Increasing the average spectral brightness by about three orders-of-magnitude will assure that such experiments (with 0.1-1 cps) become almost routine ones.

In this paper, we discuss two scenarios for an eRHIC-based X-ray FEL that promise to deliver the average brightness needed to enable this new direction in science. The range of repetition-rate of the FEL pulses in eRHIC, from 78 kHz to few MHz, and its flexible pulse structure are additional assets to this program. Fig. 3 shows the possible location of the FEL user facilities at BNL.

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*Work supported by Brookhaven Science Associates
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We briefly describe the lattice of eRHIC, and its potential performance for FEL sources. We also present a few initial simulations of possible single-pass- and OFFELO X-ray FELs.

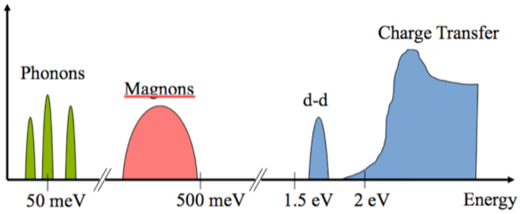

Figure 2: Typical excitation spectrum of a solid state system.

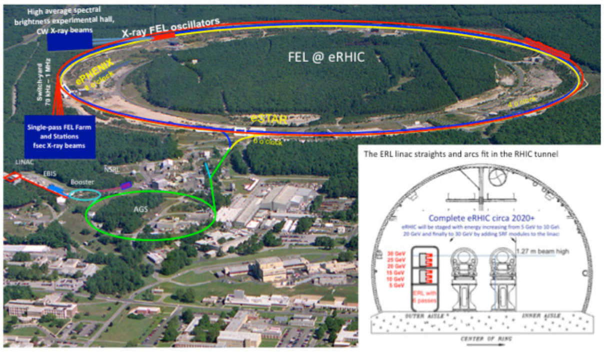

Figure 3: Possible location of FEL facilities at BNL. The insert shows proposed circulating arcs for the electron beam inside the existing RHIC tunnel.

eRHIC's LATTICE AND BEAM PARAMETERS

The ERL lattice for eRHIC comprises two 2.45 GeV 703 MHz SRF linacs, and a six-pass magnetic system. Electrons will be injected from (and ejected into) a 0.6-GeV ERL-injector. The electron beam's requirements for eRHIC vastly differ from those needed for the FEL. Thus, the FEL's electron bunches will be injected from a dedicated CW SRF photo-injector, similar to that being developed at BNL [7] for its R&D ERL. Our simulation [8] shows that such a 1/2–cell 2-MeV 703 MHz SRF photo-injector, in combination with an appropriate merger, will supply CW electron beams of very high brightness. Furthermore, increasing the SRF injector's energy to 5 MeV (by switching to 1 and ½ cell structure) promises to deliver beams suitable for operating the X-ray FEL.

One of the important challenges for multi-pass ERL is preserving the electron beam's quality (i.e., its 6-D phase-space volume).

Fig. 4 shows the acceleration sequence in one of the eRHIC linacs. Electron beams at all energies are combined to pass through the linac during the acceleration and deceleration processes. Thereafter, the beams are separated, and are bent around the arc with DC magnets tuned to their energy. For example, electron bunches coming from the 15.3 GeV arc pass through the 2.45 GeV linac. Accelerating bunches leave the linac at 17.75 GeV, and will be directed by the splitter into the 17.75 GeV arc. Simultaneously, the decelerating bunches will leave the linac with 12.85 GeV energy and will be directed by the splitter into their own arc. They will share this trip around the arc with bunches that were accelerated from 10.4- to 12.85-GeV in the linac. The average radius of the arcs of the RHIC tunnel is 381 m. Each of the six arcs will comprise 26 asynchronous cells, i.e., the lattice shown in Fig.5, providing an adjustable near-zero R_{56} [9]. 5. The splitters and combiners provide matching between the arcs and the linacs.

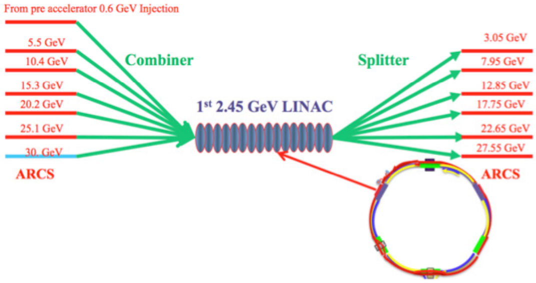

Figure 4: Acceleration- and deceleration-cycles in eRHIC ERL; only one linac is shown. The RF phase of the decelerating bunches is shifted by 180-degrees with respect to the accelerated one.

Synchrotron radiation in the arcs, the splitters, and the combiners increases the beam's energy spread and its transverse emittances. Fig. 6 shows that this eRHIC lattice preserves the beam's emittance extremely well.

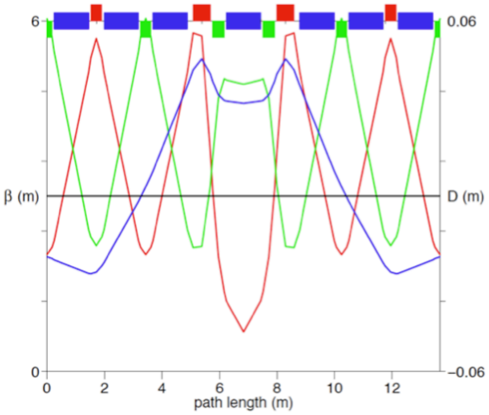

Figure 5: Isochronous (R_{56}=0) eRHIC arc lattice. Blue line – horizontal dispersion, red line – horizontal β–function, green line – vertical β–function.

Its excellent performance results from very strong focusing, and the very small value of the dispersion $|D| \le 5cm$. Even at 15.3 GeV, the normalized e-beam emittance grows only by 30 pm rad, i.e., one order-of-magnitude short of affecting FEL gain. Because the growth of normalized emittance is proportional to the energy by power seven, at energies below 10 GeV this effect simply can be neglected. Similarly, the relative growth of energy spread is modest, measuring $5.2\ 10^{-5}$ RMS for 15.3 GeV beam. Thus, we consider that the eRHIC lattice is satisfactory for supporting the beams needed for using X-ray FELs.

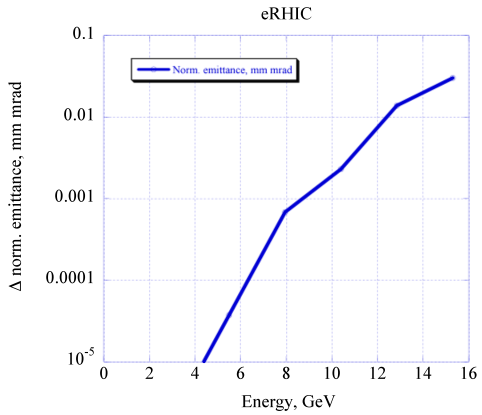

Figure 6: Growth of normalized horizontal emittance of the accelerated electron- beam in eRHIC.

Degradation of the e-beam quality can be result of various collective effects, such as coherent synchrotron radiation (CSR) and resistive-wall wakefields. The low RF- frequency of our 703 MHz SRF linac allows plan for accelerating beams with bunch-length about 2 mm RMS. With the typical 100 pC charge per bunch needed for operating the FEL, the peak current of the bunch will be only 6 A during its acceleration in the ERL. The electron bunches will be compressed to the necessary length (i.e., the kA level of peak currents) in the straight section preceding the FELs. A low- peak current in the bunches during acceleration in the ERL is the main means of avoiding beam spoiling by the CSR and the resistive-wall impedances. Our beam-dynamics studies of MeRHIC (previously considered as a 4-GeV stage of eRHIC) with 50-fold more intense electron bunches (5 nC per bunch) revealed no significant degradation of the beam's quality. We plan to undertake similar start-to-end analyses for eRHIC's beams.

FELS AT eRHIC

We are considering two types of FELs driven by eRHIC. The first will be a farm of multiple single-pass self-seeded FELs driven by a CW bunch-train from eRHIC. We will inject these trains of bunches into the abort gap of eRHIC, and eject them at several desirable energies. We will repeat the bunch-train pattern with a round-trip frequency in RHIC of 78 kHz. Downstream of the beam-line, these beams will be split and sent to individual FELs that simultaneously serve and independently operate ten-to-twenty individual FEL beam-lines. We do not plan to recover energy from these electron beams.

The following table lists various energy choices for eRHIC operation at different top energies. Table 2 shows some beam parameters and our findings from a Genesis1.3 simulation for FELs operating near 1Å wavelength. Fig. 7 shows the evolution of the peak power and resulting SASE spectrum at the end of the FEL for 7.5 GeV.

Table 1: Possible Electron Energies for FEL Beams

Top energy	e-beam energy , GeV
5 GeV	2.55, 2.96, 3.37, 3.78, 4.18, 4.59, 5.00
10 GeV	3.47, 4.28, 5.10, 5.92, 6.73, 7.55, 8.37, 9.18, 10.00
15 GeV	2.75, 3.98, 5.20, 6.43, 7.65, 8.88, 10.10, 11.33, 12.55, 13.78, 15.00
20 GeV	3.67, 5.30, 6.93, 8.57, 10.20, 11.83, 13.47, 15.10
30 GeV	3.05, 5.5, 7.95, 10.4, 12.85, 15.3

Table 2: SASE Å-scale FEL Parameters at eRHIC

Parameter	**Sample 1**	**Sample 2**	**Sample 3**
Energy, GeV	6	7.5	10
Energy spread, %	0.01	0.01	0.01
Norm. emit., mm mrad	0.4	0.4	0.4
Peak current, kA	2.7	3	3
Undulator period, cm	1.5	3	3
A_w	1.2	1	1.25
FEL wavelength, Å	1.33	1.39	1
<β>, m	9	18	18
3D gain length. m	1.61	2.59	2.87
Peak power, GW	16	15	6.8

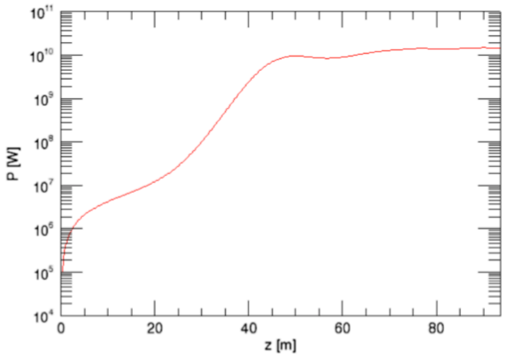

Figure 7: Peak power evolution for the 7.5 GeV case.

eRHIC single-pass FELs will have some parameters (peak power, line-width and pulse duration) similar to those of single-pass FELs driven by pulsed linacs. The high repetition rate of 78 kHz (in the dedicated mode up to few MHz) of eRHIC FEL farm sources will support about a three-orders-of-magnitude increase in average spectral brightness compared with the LCLS's projected performance, and would exceed that of the XFEL. Nevertheless, , eRHIC's FELs still will have a very different, flexible CW pulse-structure (for example, ~ 10 μsec separation between X-ray pulses) that is beneficial for some time-resolved experiments. eRHIC's CW ERL also can drive X-ray OFFELO [1,3] both in the parasitic and dedicated modes of operation. OFFELO, schematically shown in Fig.8, uses an electron beam instead of the mirror system for its feed-back. The feed-back e-beam energy is modulated by the X-ray beam exiting the high gain FEL. This modulation is preserved in the transport system, turned into density modulation at the entrance of the radiator, where it radiates coherently.

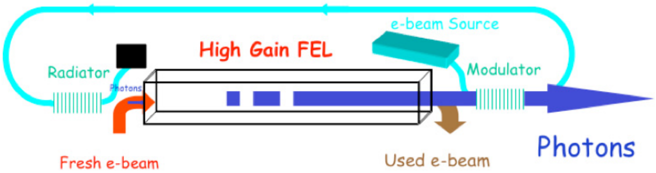

Figure 8: Schematic of OFFELO. The high gain FEL will be fed by high-energy, high peak-current (~ 10 GeV, ~ 3 kA) electron beam from eRHIC (thick red and brown arrows). The feedback will be provided by a low-energy, low peak-current (~ 0.5 GeV, ~10 A) electron beam, shown by light blue line.

This turns the e-beam in an electron –beam X-ray mirror. When lasing condition

$$G_{FEL} \cdot C_{feed-back} > 1$$

(where G_{FEL} is the FEL gain and $C_{feed-back} = P_{rad} / P_{ext}$ is the feed-back coefficient) is satisfied, the system will lase and will saturate as an oscillator. Our preliminary studies [4,10] show that such lasing is possible and that this system exhibits all features of a stable FEL oscillator with properties close to that described in the theory [11].

Since it is an oscillator, OFFELO promises X-ray beams with an extremely narrow line-width (a few ppms), and Fourier-limited fsec pulses. Since the feedback in OFFELO is provided by via a dedicated low-energy, low-current electron beam (i.e. it is optics-free) the scheme offers all the advantages of a FEL: Full tunability, and high power. Details on our plans and initial simulations for OFFELO are given elsewhere in these proceedings [4]. We plan to continue these studies and turn them in a practical design. We are discussing possibility to carry-out a proof-of-principle experiment to demonstrate an electron-beam mirror and demonstrating IR OFFELO using BNL's R&D ERL [12].

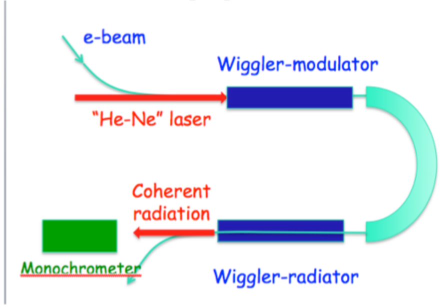

Figure 9: Schematic of an electron-mirror experiment.

Table 3: Comparison of eRHIC's FEL with Projected Performance of Å-scale FELs

Parameter	**LSLC**	**SCSS**	**XFEL**	**eRHIC, FEL farm**	**eRHIC, OFFELO**
Location	SLAC, USA	Japan	Germany	BNL, USA	BNL, USA
Status	Operational	Construction	Construction		
Reprate, Hz, NC/SC	120, NC	60, NC	10, SC	$7.8\text{x}10^4$ - 10^6	10^6
Bunches per pulse	1	1	3,000	1-100	1
FEL wavelength, Å	1.2	1	1	1	1
e-Beam energy, GeV	14.35	8	17.5	6-20	6-20
Peak brightness	$8.5\text{x}10^{32}$	$5\text{x}10^{33}$	$5\text{x}10^{33}$	$\sim 10^{33}$	$\sim 10^{33}$
Average brightness	$2.4\text{x}10^{22}$	$1.5\text{x}10^{23}$	$1.6\text{x}10^{25}$	10^{24}-10^{26}	10^{27}-10^{28}

The brightnesses listed in the table are in standard units of ph/sec/mm^2/mrad^2/0.1%BW

CONCLUSIONS

Table 3 compares our proposed eRHIC FEL parameters with sate-of-the-art X-ray FELs. FELs driven by eRHIC's ERL could increase the average brightness of spectral X-ray sources by three orders-of-magnitude above the existing and currently planned sources. BNL plans to pursue detailed analyses and several critical proof-of-principle R&D experiments to explore this unique opportunity.

The authors thank members of BNL's Accelerator Science and Technology group for stimulating discussions.

REFERENCES

[1] V.N. Litvinenko, I. Ben-Zvi, Proceedings of FEL'2004, http://jacow.org/f04/papers/WEBOS04/
[2] V.N.Litvinenko, Proc. of IPAC'10, Kyoto, Japan, May 23-28, 2010, p.2364
[3] V.N.Litvinenko, Proc. of FEL'2002 Conference, August 2002, APS, Argonne, IL, II-23
[4] Preliminary study for the OFFELO, Y.Hao, V.N.Litvinenko, these proceedings
[5] R.Walker, S.Fletcher, SRN **20**, March 2007, p.43 S.Krinsky, Accelerator Physics Challenges for the NSLS-II Project, Proc. of PAC'09, 2009
[6] P. Emma et al., Nature Photonics **176**, 2010
[7] I. Ben-Zvi et al., Proc. EPAC'08, Genoa, Italy, June 23-28, 2008, MOPC057
[8] D. Kayran, V. Litvinenko, Proc. PAC'07, Albuquerque, NM, USA, June 25-29, 2007, p.3711
[9] D. Trbojevic et al., Proc. IPAC'10, Kyoto, Japan, May 23-28, 2010, p.127
[10] V.N.Litvinenko, Optics-free X-ray FEL oscillator, 2010, http://www-conf.slac.stanford.edu/icfa2010/
[11] N.A.Vinokurov, O.A.Shevchenko, Nucl. Instr. Meth. A **528** (2004) 491
[12] D. Kayran et al., Proc. of FEL'2007, Novosibirsk, Russia, 2007, p. 232