BEAM DYNAMICS AND PERFORMANCE OF ERL-DRIVEN X-RAY FEL*

Yichao Jing†, Vladimir N. Litvinenko, Brookhaven National Lab, Upton, NY 11973, USA

Abstract

In this paper we present a self-consistent concept of ERL generated e-beam to drive an array of X-ray FELs. We use electron-Relativistic Heavy Ion Collider (eRHIC) [1] at BNL as an tool to explore all relevant beam dynamics. First, we study effects of incoherent and coherent synchrotron radiation on the e-beam parameters and present the set of parameters providing for the emittance preservation. Second, we present a single stage bunch compressing scheme with large compression ratio, which suppresses emittance growth caused by CSR. Finally, we present simulation result for soft and hard X-ray FELs driven by such electron beam. We compare projected performance of such facility with world's existing and proposed FEL facilities.

INTRODUCTION

Self-amplified stimulated emission (SASE) free electron laser (FEL) is becoming an attractive source of high-brightness photon beams. Comparing with traditional storage ring based light source, FEL has very narrow bandwidth with highly tunable central frequencies ranging in wavelength from microwaves to hard X-rays. Its peak brightness can be at least ten orders of magnitude higher than the one of storage ring. However, it is also notorious for its low repetition rate and poor stability due to shot to shot noise and fluctuations. In the recent decade, people started to use energy recovery linacs (ERLs) for FEL operation [2, 3, 4]. A single pass or multiple passes ERL can provide high quality electron beam which does not suffer from emittance and energy spread growth through effects of synchrotron radiation and microwave instabilities piling up in storage rings. At the mean time, most of the beam power is recycled before the beam goes to the dump, making a high repetition rate operation of electron beam is now possible. Such a machine could be a perfect candidate for next generation light source.

Among all the radiation wavelengths, X-rays, both soft and hard X-rays, are of great interest for many condensed matter material science and biology experiments. A multi-GeV electron beam with high peak current and low emittance is required for a high-performance X-ray FEL. Many facilities are presently constructed or being proposed while many upgrades are planned in serving this purpose [5, 6, 7, 8]. The future eRHIC ERL [9, 10] can be an excellent platform of providing such high quality electron beam as well. Although the major use of the electron beam in eRHIC is for electron hadron collision, a dedicated

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† yjing@bnl.gov

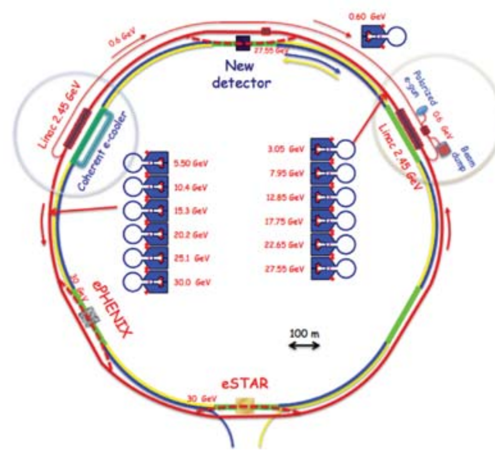

Figure 1: eRHIC layout with a 6 pass 30 GeV ERL. For FEL operation, the bunch compressor will be located at 12 o'clock, while two main linacs are at 2 and 10 o'clock respectively.

FEL operation mode could be planned. In such mode, an electron beam with extremely low emittance, low energy spread and sufficiently large bunch charge would be generated and well preserved through the beam transport to undulator. An array of X-ray FELs could be installed down stream to share the high repetition rate.

LAYOUT OF FEL OPERATION AT ERHIC

As we stated in previous seciton, eRHIC is a multi-pass ERL with a layout shown in Fig. 1. In normal routine operation, the electron beam will be accelerated in 6-pass to reach to its top energy at 30 GeV then collide with ion beams. After the collision, the electron beam energy will be recovered in the same linacs with 180 degree phase difference (decelerating mode) before going to beam dump. The entire machine has a 6-fold symmetry thus six straight sections can be used for linacs (which are located at 2 o'clock and 10 o'clock respectively) and possible experiment interaction regions.

However, for FEL operation, it is not neccessary to have a 30 GeV electron beam to get to the working regime (X-rays) we are interested in. At the mean time, to be accelerated to such a high energy, the electron beam traverses longer distances in circular passes and receives more exposure to synchrotron radiation which will result in having a larger energy spread. We choose a much lower e- beam energy (1.8 GeV – 10 GeV) allowing us to cover X-ray regime with current undulator technology. Electron beam will be injected from a different source with low normal-

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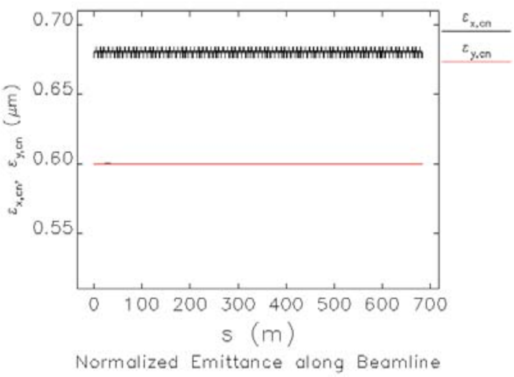

Figure 2: The e-beam emittance evolution in the eRHIC arcs. Bunch charge of 0.2 nC is used to minimized the emittance growth caused by CSR effect.

ized emittance (0.2 – 0.6 μm) and low energy spread (few tens to hundreds of keV). The beam parameters for different FEL modes can be found in Table. 1. The beam current in eRHIC arcs is kept low ($\approx$ 40 amps) mainly due to two concerns. Firstly, the synchrotron radiations (both CSR and ISR) in the circular passes require low current so that the beam emittance can be preserved through the arcs. Secondly, beam current in the ERL linacs has to stay low to avoid severe multi-pass beam breakup instability (BBU). A bunch charge at 0.2 nC seems to be a good working point for both considerations. As is shown in Fig. 2, the emittance of the circulating beam could be preserved well through the arcs.

To compress the e- beam to reach high peak current ($\sim$ kA) for FEL, a bunch compressor system will be installed in a bypass at 12 o'clock between two main linacs. Depending on radiation wavelengths, the electron bunch will be send into the bunching system on its first or second pass in eRHIC at different energies. The cavity located at 2 o'clock will be detuned from on crest operation to introduce a correlated energy spread for bunch compression. The energy spread has to be kept to a small value ($\sim 1 \times 10^{-4}$ RMS). Thus the strong compression ratio requires a large value of R_{56} in a high-field compressor. In a standard chicane a very strong coherent synchrotron radiation (CSR) would significantly deteriorate beam quality – see Fig. 3.

Table 1: eRHIC Beam Parameters for FEL Operation

Name	Soft X-ray	Hard X-ray
Energy (GeV)	1.8	10
Bunch charge (nC)	0.2	0.2
Rms bunch length (ps)	1	1
Rms energy spread (keV)	50 – 200	500
Rms normalized emittance (μm)	0.6	0.2
Undulator period (cm)	1.85	3
Wavelength of fundamental mode (nm)	1	0.1

BUNCH COMPRESSOR AND BEAM PREPARATION FOR FEL SETUP

In previous studies [11, 12], we showed that in a traditional C-type chicane CSR would blow up the beam emittance 4 to 5 - fold. The emittance growth is mainly caused by smearing of transverse phase space by the longitudinal energy variation induced by CSR wakes. Such location-sensitive energy variations induces transverse coordinate and angular displacements of particles in the transverse plane via R_{16} and R_{26} induced in the chicane. As a result, various longitudinal slices will have different coordinates and angular displacements. This, in turn, will result in smearing the distribution in the transverse phase space, and result in the projected emittance growth. As a remedy against this problem – i.e. the displacement in transverse plane due to the longitudinal energy variation induced by CSR wakes [13, 14], we propose to use two consequent chicanes with reversed bending directions, a zigzag type compressor. The opposite signs of the dispersion functions should allow to de-couple the longitudinal and transverse degrees of freedom. This technique has similarity to that has been proposed to compensate the emittance growth in ERL mergers caused by the longitudinal space charge forces [15]. We expect that in our scheme the transverse phase space displacement caused by CSR in the 1st chicane could be partially reversed in 2nd chicane. Thus the resulting emittance growth due to CSR effects could be significantly reduced. In the following sections, we study such bunch compressor design capable of compressing the beam needed for our FEL applications.

We use ELEGANT [16] code for the particle tracking including CSR effects. The evolution of beam emittance along the zigzag type of bunch compressor is shown in Fig. 4. Because bunch length is shorter in the second chicane, the CSR wakes and energy changes are stronger there. Thus the optimal cancellation of the CSR effect requires the second chicane to be weaker (about 50 % less in strength) than the first one. In addition, we adjusted the betatron phase advance between two chicanes – using two quadrupoles – for better alignment of the space phase displacement in two chicanes. As the result of such phasing the overall projected emittance was minimized. We also conducted an overall optimization process and found beta functions when the best matching could be achieved. The optimal beam line setup reduced the emittance growth to 13% in a single compressor with 15-fold bunch compression (from 40 A to 600 A). For even stronger 30-fold compressor needed to achieve 1.2 kA peak current needed for a hard X-ray FEL, a similar beam line reduces the emittance growth to 27%. The beam parameters for different machine setups are listed in Table. 2.

FEL SIMULATION AND COMPARISONS

We used Genesis 2.0 [17] to simulate the FEL processes and study the FEL power saturation in both time-resolved and time-independent simulation mode. The latter one is

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Table 2: Beam Parameters for eRHIC FEL after Bunch Compressor

Name	Soft X-ray	Hard X-ray
Energy (GeV)	1.8	10
Peak current (amp)	600	1200
Projected rms energy spread	1.15×10^{-4}	1.77×10^{-4}
Rms normalized emittance (μm)	0.678	0.253

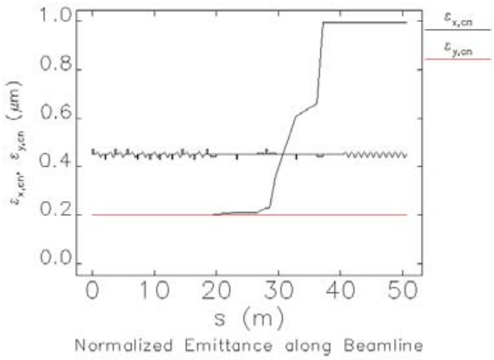

Figure 3: The e-beam emittance evolution in the bunch compressor using a single chicane. The emittance blown-up is caused by the CSR effect.

much faster and we used it to scan through the beam parameters (including optics) and to maximize the gain of FEL. We selected a LCLS type of HGFEL undulator with a few cm of period. Table. 1 lists the rest of the parameters.

We used the beam parameters at the exit of bunch compressor as input into GENESIS. We studied the tolerance on one of the most important factors the energy spread by scanning it from 50 keV to 200 keV. For statistics we used multiple random seeds at each point for the energy spread.

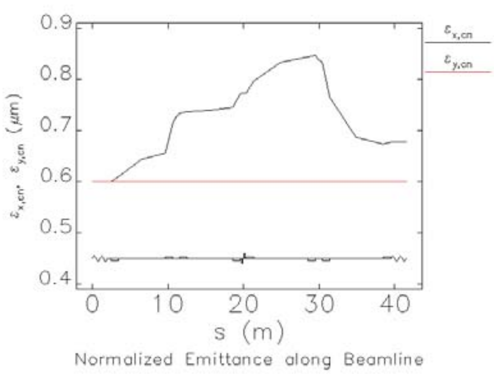

Figure 4: The e-beam emittance evolution in the bunch compressor using a Zigzag type chicane. The emittance blown-up in the first chicane due to CSR is largely compensated in the second chicane with a reversed bending magnet. The final emittance is 0.678 μm resulting in an overall13% emittance growth.

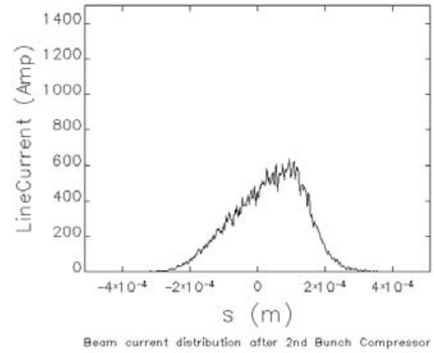

Figure 5: Final current distribution along the bunch after bunch compressor. The peak current reaches 600 amps.

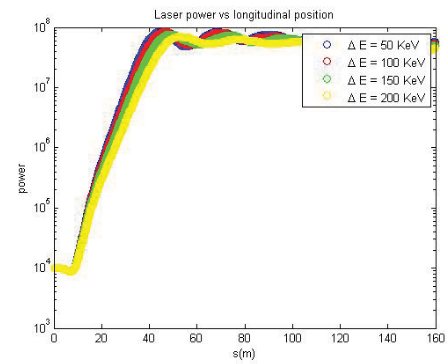

Figure 6: FEL power growth with different energy spread. Saturation can be reached at 100 m.

As seen from Fig. 6, larger energy spread tends to increase the saturation length and lower the saturation power. The fitted 3D gain length dependence on the energy spread is shown in Fig. 8. For the energy spreads of interest, the 3D gain length is quite short ($\sim$ 2 m) allowing us to reach saturation in less than 100 m. However, as is shown in Fig. 7, the saturation power drops about 30% with the increase of the energy spread.

Table. 3 compare our proposed eRHIC FEL parameters with state of the art X-ray FELs. FELs driven by eRHICs ERL could increase the average spectral brightness in X-ray range up to three orders-of-magnitude above the existing and currently planned sources.

DISCUSSION

We used time-independent Genesis simulation for our optimization study of FEL farm at eRHIC. The time resolved simulations are very time consuming and we did not used them for parameter scanning. Few initial time dependent simulations are being carried out for two specific cases (1.8 GeV 1 nm and 10 GeV 1 A). These simulation are in good over-all agreement with the time-independent

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Table 3: Comparison of eRHICs FEL with Projected Performance of X-ray FELs

Parameter	**LCLS**	**SCSS**	**XFEL**	**eRHIC,Hard X-FEL**	**eRHIC, Soft X-FEL**
Energy (GeV)	14.35	8	17.5	10	1.8
Rep rate (Hz)	120	60	10	1×10^6	1×10^6
FEL wavelength (Å)	1.2	1	1	1	1×10^3
Peak brightness (ph/sec/mm^2/mrad^2/0.1%BW)	8.5×10^{32}	5×10^{33}	5×10^{33}	$\sim 10^{33}$	$\sim 10^{33}$
Average brightness (ph/sec/mm^2/mrad^2/0.1%BW)	2.4×10^{22}	1.5×10^{23}	1.6×10^{25}	$10^{26} - 10^{29}$	$10^{26} - 10^{29}$

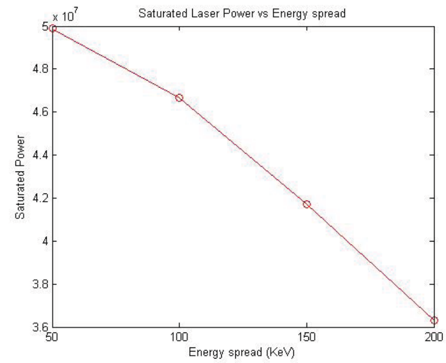

Figure 7: The saturation power with various energy spread. Power drop mainly comes from the decrease of ρ_{fel}

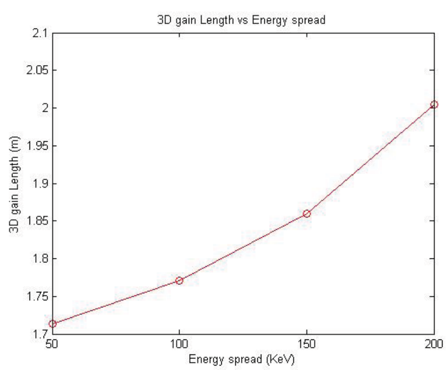

Figure 8: Fitted 3D gain length with various energy spread. The gain length stays below 2 m with various energy spread setups enabling us to get saturated signal at 100 m.

simulations. Extensive details of these simulations will be published elsewhere.

CONCLUSION.

We studied various possible operation modes for FEL farm based on the future eRHIC ERL. We demonstrated that high quality electron beam could be preserved through the machine. We proposed and simulated a Zigzag type bunch compressor, which greatly reduces CSR-induced emittance growth. Our FEL simulations show that electron beam prepared by such compressor is well suited for both soft- and hard-X-ray FELs. If realized, eRHIC driven FEL would increase average spectral brightness of the X-ray FEL sources by about three orders of magnitude.

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