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ERL-BASED COMPACT X-RAY FEL*

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Abstract

We propose to develop an energy-recovery-linac (ERL)-based X-ray free-electron laser (XFEL). Taking advantage of the demonstrated high-efficiency energy recovery of the beam power in the ERL, the proposed concept offers the following benefits: i) recirculating the electron beam through high-gradient superconducting RF (SRF) cavities shortens the linac, ii) energy recovery in the SRF linac saves the klystron power and reduces the beam dump power, iii) the high average beam power produces a high average photon brightness. In addition, such a concept has the capability of delivering optimized high-brightness CW X-ray FEL performance at different energies with simultaneous multipole sources. In this paper, we will present the preliminary results on the study of feasibility, optics design and parameter optimization of such a device.

INTRODUCTION

A Free-Electron Laser (FEL) that has been invented and experimentally demonstrated in the 1970s [1, 2] holds a great potential to serve as a high-power and coherent photon source. FEL performance extends beyond the limitations of fully coherent laser light sources by covering a broad range of wavelength from infrared down to X-ray with a stable and well-characterized temporal structure in the femtosecond time domain. Particularly, XFEL allows scientists to probe the structure of various molecules in detail, and simultaneously explore the dynamics of atomic and molecular processes on their own time scales.

Techniques have been developed and improved to amplify the spontaneous radiation to provide intense quasi-coherent radiation [3-6]. The FEL process strongly depends on the local electron beam properties: current, energy, emittance and energy spread. Therefore, all existing XFELs [7-15] are driven by linear accelerators to ensure preservation of the electron beam quality from the source for achieving a high peak brightness. Normal conducting RF cavities, with very high accelerating gradients of up to 60 MV/m, are used to keep the linac length as short as possible. This limits the bunch repetition rate up to about 100 Hz in a pulsed beam operation mode, resulting in average photon brightness of as much as 10 orders of magnitude lower than the peak one. Therefore, several XFEL facilities [9, 13] have started considering a CW beam operation mode that is made possible by the high-gradient SRF technology. There were two ERL-based concepts [16, 17] explored to produce FELs in the UV and/or soft X-ray regions.

CONCEPT

We propose an ERL-based compact XFEL facility, schematically illustrated in Fig. 1. Note that the energy gain of 2 GeV from the SRF is chosen for this study only, considering relatively realistic SRF gradient, magnet fields, and geometric footprint of such a facility. Optimization of these parameters can be carried out in each individual case. We leverage the ongoing world-wide efforts on the further improvement of injector and XFEL techniques and focus on the feasibility study of the accelerator system.

Electron beams are generated from the source and accelerated to 250 MeV before the first bunch compression (BC). Then the beams are accelerated in the ERL by SRF cavities with the desired energy gain of 2 GeV. Since space charge effects are significantly suppressed at the GeV electron beam energy, one can utilize the first arc to compress the beam for the second time if needed. The electron beams are either directed into different undulators that can be designed and optimized for particular XFEL radiations parameters or bypass the undulator sections. Electron beams that have been used to produce XFEL can be energy recovered in the ERL after the second arc and dumped downstream. The bypassed electron beams will double energy up to ~ 4 GeV after the ERL and propagate through the third arc. Same as in the first ~ 2 GeV energy loop, the ~ 4 GeV electron beams will either be directed into different undulator sections or bypass the undulators. Again, the electron beams that have produced XFEL will be energy recovered and dumped, and the bypassed electron beams will be further accelerated to ~ 6 GeV for XFEL production and energy-recovered in the ERL before the final dump.

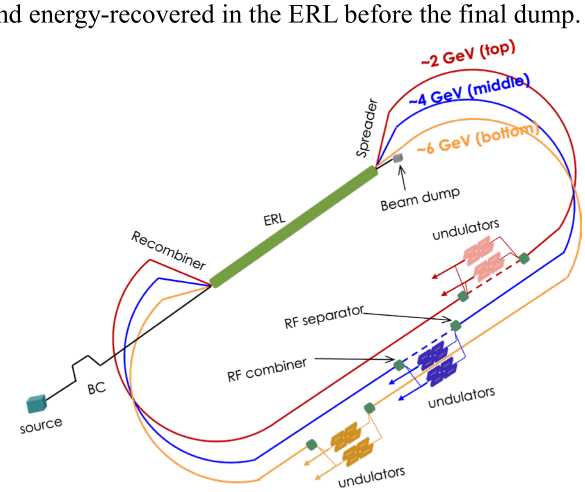

Figure 1: Schematic drawing of the proposed ERL-based XFEL facility.

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When a practical working limit of 1 MW dump beam power is considered, the first ERL injection beam energy of 250 MeV results in an average electron beam current of 4 mA. Comparing to the pulsed beam operation mode with the average beam current at the level of a few tens of nA, the CW beam operation mode will boost the average photon brightness significantly. A high bunch repetition rate of several to tens of MHz can produce a mA average beam current with a modest bunch charge. Small charge per bunch allows a short bunch length and a small transverse emittance. For this reason, it is easier to stabilize the beam energy and minimize the energy spread in a CW SRF system than a pulsed normal RF system that may have a reproducibility issue.

In addition to the improving the XFEL performance, this concept minimizes the power consumption by returning the energy back to the SRF cavities and then reusing it to accelerate the subsequent low energy beams. An energy recovery efficiency of up to 90-99% can be reached according to current development of SRF technology. Besides, the operating cost of the SRF cavities with nearly zero resistive wall losses is much lower than that of the normal conducting RF cavities in the CW mode.

OPTICS

Synchrotron radiation (SR) occurs when electrons propagate through dipoles in an accelerator. Incoherent synchrotron radiation (ISR) refers to the SR power emitted in a fully incoherent region in a dipole magnet. Particle's motion experiences diffusion and excitation from the ISR, resulting in a growth of emittance $\Delta\epsilon_u$ and energy spread $\Delta(\sigma_E^2)$ along the path of length L:

$$\Delta(\sigma_E^2) = \frac{55\alpha(\hbar c)^2}{48\sqrt{3}}\gamma^7 \int_0^L \left(\frac{1}{|\rho_x^3|} + \frac{1}{|\rho_y^3|}\right) ds, \quad (1)$$

$$\Delta\epsilon_u = \frac{55 r_c \hbar c}{48\sqrt{3} mc^2}\gamma^5 \int_0^L \frac{H_u}{|\rho^3|} ds. \quad (2)$$

Here γ is the Lorentz factor and ρ is the dipole magnet bending radius in any $u = x\ or\ y$ plane. Growth of electron beam emittance and energy spread is proportional to the 5th and 7th power of energy, respectively, and inversely proportional to the bending radius. In addition, the change of emittance also depends on the accelerator optics design, characterized by the H function with $H_u = \beta_u D_u'^2 + 2\alpha_u D_u D'_u + \gamma_u D_u^2$.

As the FEL process strongly depends on the local electron beam properties, an optimum accelerator design should have minimal growth of the electron beam emittance and energy spread during its propagation from the source to the undulators. Once the electron beam energy is chosen, only the dipole bending radius and optics design are left to be optimized to control the beam properties. From the optics design point of view to reduce the growth of emittance, the horizontal beta function and dispersion need to be suppressed in dipoles, assuming horizontally bending dipole magnets. A large dipole bending radius ensures a small growth in emittance and energy spread of electron beams. However, this results in an increased circumference of an accelerator and its footprint. Therefore, an ultimate design goal of the proposed ERL-based XFEL facility will be preservation of the electron beam quality while making the accelerator facility as compact as possible.

Several arc cell optics designs have been explored extensively. Figure 2 (left) shows the preliminary arc cell lattice. This cell has phase advances of $(\phi_x, \phi_y) = (\frac{5\pi}{2}, \frac{3\pi}{2})$ for better control of sextupole-induced nonlinear resonances and the isochronous condition of $M_{56} = 0$ for better control of CSR-induced emittance growth. To simplify the front-to-end optics for studying electron beam dynamics, the following assumptions are made: i) the same arc cell optics is applied to construct all six arcs at three different electron beam energies, ii) straights for ERL and undulators are filled with FODO cells as space holders, iii) cavities are treated as zero-length elements with appropriate phases for acceleration or deceleration of the beams, iv) path length adjustment, spreader/recombiner sections are not implemented but have been demonstrated in existing accelerator facilities. All these detailed features will be added to design later, however, they should not have a significant impact on the beam dynamics.

A complete lattice optics and its footprint are plotted in Fig. 2 as well.

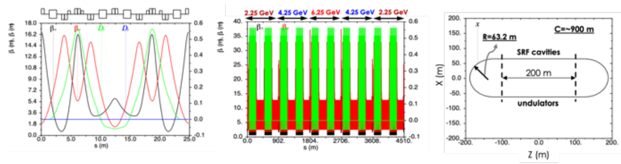

Figure 2: (Left) Arc cell optics. (Middle) Complete lattice optics. (Right) Footprint of the design.

BEAM DYNAMICS

Incoherent Synchrotron Radiation (ISR)

Tracking simulations are carried out to study the degradation of electron beam quality due to ISR. Particles are generated at 2.25 GeV with normalized horizontal emittance $\epsilon_x^N = 0.25$ µm and energy spread $\Delta E = 0.1$ MeV. Figure 3 illustrates the locations, in terms of the beam energy, where the particle phase space distributions are plotted in Figs. 4 and 5.

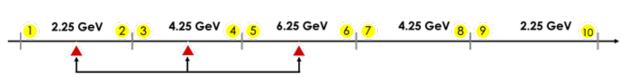

Figure 3: Locations in the unfolded beamline where the particle distributions are plotted in Figs. 4 and 5.

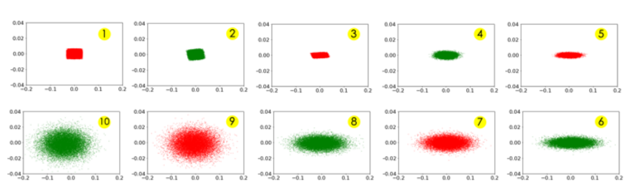

Figure 4: Evolution of the particle distribution in the (x, x') phase space. (x in mm, x' in mrad).

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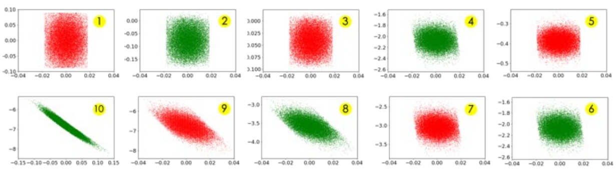

Figure 5: Evolution of the particle distribution in the (z, δ) phase space. (z in mm, $\delta = \delta \times 10^{-3}$).

Note that all particles survive during the tracking simulation under the condition of no compensation of the energy loss due to the synchrotron radiation. This results in the center momentum of the beam being shifted as shown in Fig. 5 and chirping effect from RF cavities occurring and being enhanced in the energy recovery loops.

Table 1 lists the unnormalized horizontal emittance ϵ_x and the relative energy spread $\delta = \Delta E/E$ at several energies of interest. Both the emittance and energy spread are well preserved at 2.25 and 4.25 GeV at the locations of the undulators with help of damping due to increase in the electron beam energy. Because of their strong energy dependence, these two quantities degrade significantly at the proposed highest energy of 6.25 GeV. However, the degradation can be suppressed in by optics optimization using a relatively large dipole bending radius while keeping the footprint compact.

Table 1: Unnormalized Horizontal Emittance ϵ_x and Relative Energy Spread δ at Several Energies of Interest

Energy (GeV)	**Location**	δ (10^{-5})	ϵ_x (10^{-12} m)
2.25	Initial	3.91	43.7
2.25	Undulators	3.97	44.1
4.25	Undulators	3.92	31.4
6.25	Undulators	9.30	81.3

Coherent Synchrotron Radiation (CSR)

CSR poses a significant challenge for FEL-driven accelerators with high brightness beams. Rather than the more conventional head-tail instabilities where the tail is affected by the actions of the head, CSR is a tail-head instability. The tail of the beam loses energy while the head gains energy, leading to an undesirable redistribution of the particles in the bunch. With a short bunch length desired in FELs to increase the electron bunch peak current and the peak brightness of photons, CSR has a serious impact on the beam quality that may be critical for the success of FELs. Three sets of parameters, listed in Table 2, are used to explore the CSR effect on the beam quality at the lowest energy of 2.25 GeV. The parameters in the "SASE" case are similar to those in the LCLS-II design [9]. The "SASE-like" case is similar to "SASE" but provides an extended bunch length. The "XFELO" case parameters are from K.J. Kim [18].

Figures 6 shows the particle horizontal and longitudinal phase space distributions resulting from tracking simulations at the end of the 2.25 GeV arc. Due to its extremely short bunch length of 9 µm (30 fs) rms, the "SASE" case has the horizontal emittance and energy spread increased by a factor of up to several orders of magtitude. With the same bunch charge but a longer rms bunch length of 30 µm (100 fs), the "SASE-like" case has no emittance growth in the horizontal plane and about ten times emittance growth in the longitudinal plane. The "XFELO" case has the least CSR effect on the beam quality among these three cases. There is no horizontal and only modest longitudinal emittance growth. The CSR effect can be further reduced through the same optics optimiztion that wsa used to suppress the ISR effect on the beam quality.

Table 2: Beam Parameters for Studying the CSR Effect at the Lowest Energy of 2.25 GeV

Cases	**Unit**	SASE	SASE-like	XFELO
Energy	GeV		2.25	
Initial rms ϵ_x^N	µm		0.3	
Initial rms δ	10^{-5}		4.4	
Charge per bunch	pC	30	30	100
Bunch length rms	µm	9	30	120

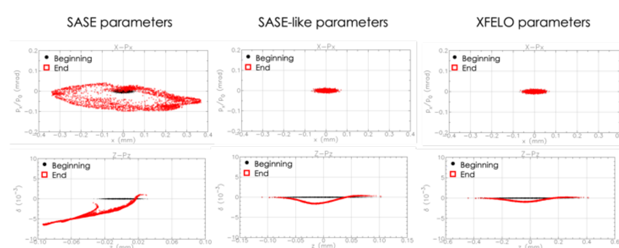

Figure 6: Particle phase space distributions in the horizontal and longitudinal planes.

CONCLUSION

We explore the design feasibility of an ERL-based XFEL. Several arc cell optics are explored to optimize the beam quality and the facility footprint. Complete preliminary linear optics is established, and beam dynamics study is performed. Growth of the beam horizontal emittance and energy spread, due to both incoherent and coherent synchrotron radiation is modest. Further optics and parameter optimization will be carried out to suppress degradation of the beam quality. Potential R&D aspects will be identified as well.

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REFERENCES

[1] J. Madey, "Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field", *J. Appl. Phys.*, vol. 42, p. 1906, 1971. doi:10.1063/1.1660466

[2] D. A. G. Deacon, L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith, "First Operation of a Free-Electron Laser", *Phys. Rev. Lett.*, vol. 38, p. 892, 1977. doi:10.1103/PhysRevLett.38.892

[3] A. M. Kondratenko and E. L. Saldin, "Generation of coherent radiation by a relativistic electron beam in an undulator", *Particle Accelerators*, vol. 10, pp. 207-216, 1980.

[4] L.-H. Yu *et al.*, "High-Gain Harmonic-Generation Free-Electron Laser", *Science*, vol. 289, no. 5481, pp. 932-934, 2000. doi:10.1126/science.289.5481.932

[5] M. Ferray *et al.*, "Multiple-harmonic Conversion of 1064 nm Radiation in Rare Gases", *J. Phy. B: Atomic, Molecular and Optical Physics*, vol. 21, p. L31, 1988. doi:10.1088/0953-4075/21/3/001

[6] K-J. Kim *et al.*, "A Proposal for an X-Ray Free-Electron Laser Oscillator with an Energy-Recovery Linac", *Phys. Rev. Lett.*, vol. 100, p. 244802, 2008. doi:10.1103/PhysRevLett.100.244802

[7] G. Geloni, Z. Huang, and C. Pellegrini, "The Physics and Status of X-ray Free-electron Lasers" in *X-Ray Free Electron Lasers: Applications in Materials, Chemistry and* Biology, U. Bergmann, V. K. Yachandra, and J. Yano, Royal Society of Chemistry, 2017, pp. 1-44. doi:10.1039/9781782624097-00001

[8] "Linac Coherent Light Source (LCLS) Conceptual Design Report", SLAC, CA, USA, SLAC-R-593, Apr. 2002.

[9] "Linac Coherent Light Source (LCLS-II) Conceptual Design Report", SLAC, CA, USA, SLAC-R-978, Apr. 2011.

[10] M. Yabashi, "Status and future of SACLA: the Japan's X-ray Free-Electron Laser", *Research in Optical Sciences*, p. IW1D.1, 2012. doi:10.1364/ICUSD.2012.IW1D.1

[11] T.-Y. Lee *et al.*, "Overview of PAL-XFEL", *AIP Conference Proceedings*, vol. 879, p. 252, 2007. doi:10.1063/1.2436049

[12] E. Prat *et al.*, "A Compact and Cost-effective Hard X-ray Free-Electron Laser Driven by a High-brightness and Low-energy Electron Beam", *Nature Photonics*, vol. 14, pp. 748-754, 2020. doi:10.1038/s41566-020-00712-8

[13] European XFEL, https://www.xfel.eu/facility/overview/index_eng.html

[14] Free-Electron Laser FLASH, https://flash.desy.de/.

[15] FERMI lightsource, https://www.elettra.trieste.it/lightsources/fermi.html

[16] The JLAMP VUV/Sorft X-ray User Facility, http://www.jlab.org/FEL/jlamp/JLAMP_Proposal.pdf

[17] M. W. Poole, J. A. Clarke, and E. A. Seddon, "4GLS: An Advanced Multi-Source Low Energy Photon Facility for the UK", in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper TUPLE001, pp. 733-735.

[18] K. J. Kim, "X-Ray FEL Oscillator", CERN Accelerator School, Hamburg, Germany, 2016.