5 upgradable to 25 keV free electron laser facility

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A free electron laser (FEL) facility utilizing a recirculated superconducting radio frequency (SRF) electron linear accelerator (linac) provides the opportunity to achieve about 5 times greater photon energy than an unrecirculated linac facility of similar cost. An electron linac configuration utilizing a 4 GeV unrecirculated, SRF linac could be used to drive a FEL producing 5 keV photons. However, for a similar cost, a recirculated SRF linac system can deliver the 4 GeV electrons for photon energies of 5 keV and provide an upgrade path to photon energies of 25 keV. Further support amounting to about a third of the initial investment would provide additional recirculated SRF linac and cryogenic capacity sufficient to deliver electron energies appropriate for 25 keV photons matching the European XFEL.

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I. INTRODUCTION

In July 2013, the Department of Energy (DOE) Basic Energy Sciences Advisory Committee (BESAC) issued a report [1] recommending a high duty factor, continuous wave (cw) free electron laser (FEL) with photon energies of about 5 keV. With appropriate siting, an initial implementation strategy could be the realization of the 5 keV facility with an upgrade path to a world-class, scientifically important 25 keV cw facility. (See, for example, Reference [2].)

Two design concepts for an electron beam accelerator suitable for a 5 keV FEL and upgradable to a 25 keV FEL are possible.

A single-pass superconducting radio frequency (SRF) cw electron linac of 4 GeV would provide 5 keV photons. In principle, an additional 5.2 GeV of single-pass SRF cw electron linac could be later implemented downstream of the first linac providing 9.2 GeV electrons appropriate for photons of about 25 keV. This linear configuration would allow the electron beam to be bunched during acceleration to achieve the high peak beam current and beam emittance preservation appropriate for an efficient FEL process. The primary penalty of this approach is the cost and size of the SRF linac system including both the accelerating structures and necessary cryogenic plant with the upgrade step to 25 keV photons requiring an additional 5.2/4 or 130% of the initial implementation.

Alternatively, a recirculated SRF cw electron linac configuration can be used to produce the initial 4 GeV electrons with sufficient space provided for later addition of recirculated linac necessary to achieve 9.2 GeV. For an efficient FEL process, the electron beam transverse emittance and peak current must be appropriate. During recirculation, the beam transverse emittance preservation relies on long bunch lengths (low peak current, tens of ampere) and careful magnetic optics design using a large magnetic bend radius. After recirculation, the beam must then be bunched to achieve high peak currents (kiloamps) while preserving the transverse emittance.

II. FEL DESIGN ISSUES

With a conventional planar magnetostatic undulator, the FEL process generates a photon wavelength λph given by

$$\lambda \mathrm{ph} = [\lambda \mathrm{u} \cdot (1 + \mathrm{K}^2/2)]/(\mathrm{h} \cdot 2 \cdot \gamma^2), \tag{1}$$

where $\gamma = (\text{electron kinetic energy/electron mass} + 1)$, $\lambda\mathrm{u} =$ undulator period. For a magnetostatic undulator $K = 0.934 \cdot B(T) \cdot \lambda\mathrm{u(cm)}$ with $B =$ undulator on-axis magnetic field, and $h =$ harmonic $(1, 3, 5\ldots)$ of the photon radiation.

The envisioned FEL-based science program is best realized with a cw linac providing more stable and precise photon delivery at nondestructive levels compared to a low duty factor linac. The primary cost element for a cw FEL is the SRF linac. From Eq. (1), the necessary linac energy to achieve a specific photon energy can be reduced as $(\lambda\mathrm{u})^{1/2}$, but for magnetostatic undulators, λu have only been reliably developed to ~cm level with reasonable K values, which determine the FEL gain.

In addition, there is a beam quality requirement that the electron beam necessary to achieve optimal FEL performance must be correlated with λph as

$$\varepsilon_\mathrm{G} = \varepsilon_\mathrm{N}/\gamma \leq \lambda\mathrm{ph}/(4\pi), \tag{2}$$

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where $\varepsilon_G =$ geometric emittance and $\varepsilon_N =$ normalized emittance.

Therefore, utilization of lower energy electrons has the associated requirement of a smaller ε_N given the reduced γ.

The longitudinal beam parameter ($\Delta\gamma/\gamma$) has a similar beam quality requirement of

$$\Delta\gamma/\gamma < \rho_{\mathrm{FEL}} \tag{3}$$

with

$$\rho_{\mathrm{FEL}} = (1/4\gamma)\cdot[Ipk\cdot\lambda u^2\cdot K^2\cdot[\mathrm{JJ}]^2)/(IA\cdot\pi^2\cdot\varepsilon_{\mathrm{G}}\cdot\beta f)]^{1/3}, \tag{4}$$

where $\rho_{\mathrm{FEL}} =$ FEL Pierce parameter, $Ipk =$ peak beam current, $[\mathrm{JJ}] =$ Bessel function factor for planar undulator, $IA =$ Alfen current, and $\beta f =$ machine beta function.

III. SRF LINAC DESIGN ISSUES

The cw requirement of the BESAC report [1] dictates utilization of an SRF linac. For a low duty factor SRF linac, the lowest cost system will have the highest accelerating gradient that can be reliably achieved. In contrast, for a cw SRF linac, system cost assuming present or near-term achievable parameters will have a minimum for an accelerating gradient in the range of 15 to 20 MV/m.

For beam currents appropriate for an FEL, an SRF linac if only accelerating a single beam is lightly beam loaded. In addition, the cost of an SRF linac scales as the number of accelerating sections. Recirculating the electron beam provides higher more efficient beam loading and reduces the number of accelerating systems and cost necessary to achieve a given electron energy. However, as discussed, the beam recirculation and associated bunch length compression systems must preserve beam quality at a level appropriate for efficient FEL performance.

The cryogenic plant capacity and cost for an SRF linac of fixed energy scales linearly with cavity gradient and inversely with number of accelerating structures and cavity quality factor (Q_0). Recirculation reduces the number of accelerating structures and therefore the necessary cryogenic plant capacity. Increasing the Q_0 design value reduces the necessary cryogenic plant capacity but also increases the technical risk that the design Q_0 will not be obtained.

The high Q_0 of SRF structures infers an unacceptably narrow resonance that is mitigated by a substantially lower loaded Q (Q_L). A lower Q_L provides a broader bandwidth and concomitant reduction in performance risks caused by cavity motion due to mechanical vibrations. However, the rf drive necessary and its cost increase with lower loaded Q_L. Therefore, the better feedback performance of a single rf drive per single cavity topology is important especially in light of the demand for high beam quality commensurate with high FEL efficiency. In addition, a single rf drive per single cavity topology offers the opportunity to optimized individual cavity performance.

IV. DESIGN CONCEPT

The design goal is a recirculated cw SRF electron linac system that initially provides electron energies of up to 4 GeV for an FEL system producing 5 keV photons and that can be straightforwardly upgraded to provide electron energies of 9.2 GeV for an FEL system producing 25 keV photons.

The design is based on the existing Jefferson Lab (JLab) 12 GeV upgrade, 1.5 GHz, cryomodule providing an energy gain of 100 MeV in a length of ~10 m including an intracryomodule warm region for diagnostics and transverse focusing. The cavity gradients are about 20 MV/m with a Q_0 of 8×10^9 at 2 K. Though some improvements like e.g., intracell stiffening rings, should be made, this cryomodule is largely appropriate for the required cw application and provides realistic values for cryogenic loads and costing. The 12 GeV upgrade cryomodule system has well controlled microphonics and the ability for overall optimization of individual cavity performance with the low level rf control using the topology of a single klystron per accelerating structure. The 12 GeV upgrade cryomodule system supports acceleration of a total beam current of up to ~1 mA, but if necessary a rf coupler redesign and increased klystron power would provide a substantial increase in current capability. For a microbunch frequency of 2.5 MHz, the recirculated beam parameters of Table I would result in a total accelerated beam current of 1 mA given the proposed four-pass recirculation.

The recirculation topology (see Fig. 1) is similar to that of JLab with a linac, spreader, recirculation, recombination sequence and a microbunch-by-microbunch-based extraction system utilizing rf separators. Different from JLab is the utilization of a single recirculated linac with separate return legs between the two arcs reducing by half the amount of beam spreading and recombining per pass and thereby reducing the potential for loss of beam quality. It is envisioned that multiple FELs will follow the microbunch-by-microbunch extraction segment with a photocathode electron gun providing microbunches optimized for individual users. The recirculated linac configuration shown in Fig. 1 has an approximate footprint of ~300 × ~770 m (~57 acres).

TABLE I. Recirculated linac beam parameters.

Recirculated linac beam parameters	Value
Input normalized emittance (mm-mrad)	0.35
Charge per bunch (pC)	100
Bunch length (ps)	2
Peak current (A)	50
Bend radius (m)	100

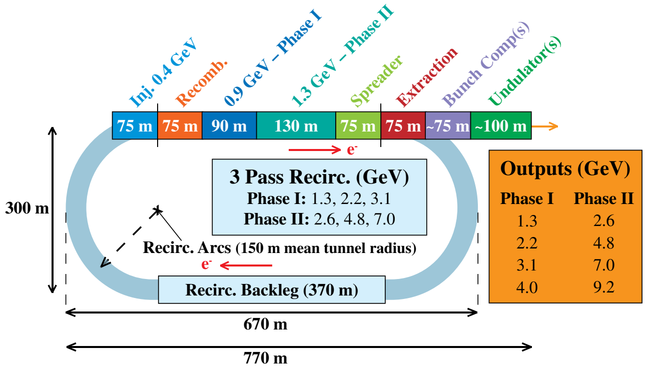

FIG. 1 (color online). Conceptual layout of a recirculated SRF linac for a 5 keV upgradable to a 25 keV FEL facility. Phase I implementation includes full civil construction and 1.3 GeV of SRF linac with a cryogenic facility providing output energies of 1.3, 2.2, 3.1, and 4 GeV. Phase II implementation includes another 1.3 GeV (2.2 GeV total) of recirculated linac and an additional cryogenic plant facility providing output energies of 2.6, 4.8, 7.0, and 9.2 GeV.

From JLab 12 GeV upgrade data, the total SRF linac energy of 2.6 GeV of Fig. 1 is compatible with two cryogenic plants each with a capacity of the largest transportable (~18 kW at 4.5 K) unit for a total of ~35 kW at 4.5 K. The proposed execution sequence is for phase I to implement the full conventional facility necessary for Fig. 1 but only installing 0.9 GeV of the 2.1 GeV recirculated linac. This will require only one cryogenic plant and provide output energies of approximately 1.3, 2.2, 3.1, and 4.0 GeV. (Not counting the undulators, phase I implementation including the cost of civil construction is estimated to be comparable to the cost of an unrecirculated 4 GeV SRF linac including the appropriate cryogenic plant but with no civil construction excepting that necessary to house the cryogenic plant.) At a later date, an additional 1.3 GeV of recirculated linac and its cryogenic plant could, for only an additional one-third of the initial investment, be straightforwardly implemented in the existing tunnel and klystron gallery providing the phase II layout of Fig. 1.

The Stanford Linear Accelerator Center (SLAC) Linear Coherent Light Source (LCLS) gun is not capable of cw performance, but it does, however, provide a point of comparison for possible enhanced performance cw guns of the future. The value of ε_N varies as a function of the charge per microbunch. In the low charge regime, the thermal dominates with the emittance scaling as the charge per bunch to the one-third power. From Ref. [3], the normalized emittance is given as

$$\varepsilon_N \approx \text{constant}(0.111 Q^{2/3} + 0.18 Q^{4/3} + 0.18 Q^{8/3})^{1/2}, \quad (5)$$

where the constant is empirical (a value of 1.4 is consistent with the LCLS results), giving the normalized emittance ε_N (mm-mrad) as a function of charge per bunch $Q(C)$. For a charge per bunch of 100, 200, and 300 pC (pico-coulomb), the SLAC gun provides ε_N of 0.25, 0.35, and 0.43 mm-mrad respectively.

TABLE II. Parameters assumed at the FEL undulator.

Parameter at FEL undulator	Value
Charge per bunch (pC)	100
Bunch length (fs)	65
Peak current (kA)	1.5
Undulator period (cm)	2
Undulator parameter K (planar)	1
Electron energy spread (keV)	500

Electron guns appropriate for a cw high frequency (~1 MHz) microbunch structure are under development utilizing room temperature technology at Lawrence Berkeley National Laboratory [4] and SRF technology at University of Wisconsin [5] with results compatible with an ε_N of 0.35 mm-mrad for a charge per bunch of 100 pC.

For the analysis presented, the values of Table I were utilized for the electron beam parameters of the recirculated linac and the values of Table II were employed for electron beam parameters at the FEL undulator. From Eq. (1), a planar undulator with λu of 2 cm, and K of 1 with an electron beam energy of 4 GeV or 9.2 GeV, provides λph of 0.245 nm (photon energy of 5 keV) or 0.046 nm (photon energy of 26.8 keV), respectively. For these parameters, Eq. (2) would require that $\varepsilon_N \sim 0.15$ and ~0.07 mm-mrad for 5 and 26.8 keV, respectively. Given in Table I, a value of 0.35 mm-mrad was assumed for the input normalized emittance. The Ming Xie formalism [6] was used to determine the effect of finite electron beam emittance and energy spread including increases from coherent and incoherent synchrotron radiation on the length of undulator necessary to achieve saturation as given in Table III.

The design is based on two considerations.

First, the electron beam can be recirculated while maintaining the beam quality sufficient to support an efficient FEL process by utilizing a large (150 m) arc tunnel radius and having a modest (few degrees rf ~2 ps) bunch length during recirculation. A bending radius of 100 m is compatible with a gross arc radius of 150 m.

The deleterious effects of coherent synchrotron radiation (CSR) can be suppressed using techniques described by DiMitri, Cornacchia, and Spampinati [7]. CSR causes negligible (~0.1%) contributions to the beam emittance given a beam a bunch length of 2 ps with up to 2 times the charge per microbunch (200 pC) of Table II.

Using a theoretical minimum emittance-based recirculator arc [8], the incoherent synchrotron radiation (ISR) will, for the case of 4 GeV phase I, generate an increase in the normalized emittance of <0.002 mm-mrad and a rms momentum spread of 2.2×10^{-6}. Then ISR will cause no

TABLE III. Photon energy for electron energies of Fig. 1, and using Ming Xie formalism [6], the undulator length necessary for saturation given parameters of Tables I and II. The normalized emittance at the undulator is from (input normalized emittance plus increase from ISR)×1.3 (emittance increase from bunch compression). An average machine beta function βf of 10 m was used for electron energies up to 4.8 GeV and 40/50 m for electron energies of 7.0/9.2 GeV, respectively.

Electron energy (GeV)	Photon energy (keV)	ε_N (mm-mrad)	ρ_{FEL}	Undulator saturation length (m)
1.3	0.54	0.46	11.7×10^{-4}	20
2.2	1.5	0.46	8.2×10^{-4}	27
2.6	2.1	0.46	7.4×10^{-4}	31
3.1	3.0	0.46	6.5×10^{-4}	36
4.0	5.0	0.46	5.5×10^{-4}	46
4.8	7.3	0.47	4.9×10^{-4}	60
7.0	15.5	0.62	2.2×10^{-4}	127
9.2	26.8	0.67	1.6×10^{-4}	206

performance issues for phase I. The ISR will, for the case of 9.2 GeV phase II, generate an increase in the normalized emittance of 0.17 mm-mrad and in the rms momentum spread of 1.6×10^{-5} [9,10,11,12].

Second, the bunch quality during recirculation is maintained by retaining a bunch length of order ps. As a consequence, to obtain the peak current appropriate for an FEL, the electron bunch length must be reduced from ps to tens of fs by compression after acceleration. A recent publication [13] proposes a bunch compression scheme that for the case of 10 GeV electrons, rms energy spread of 500 keV, and a bunch charge of 200 pC provides a compression factor of 30 resulting in a peak current of 1.2 kA with a transverse emittance growth of <30%. A similar result for our case would reduce a 2 ps bunch length to ~65 fs providing a peak current of 1.5 kA as given in Table II.

Table III provides, for the electron energies of Fig. 1 and parameters of Table I and Table II, the normalized emittance including the effects of ISR and bunch compression, and using the Ming Xie formalism [6], the undulator length necessary to achieve saturation.

V. NEXT STEPS

A refined parameter list including those of Tables I, II, III, injection energy, recirculated linac energy, recirculation bend radius, and bunch compression and seeding schemes among others can largely be quantitatively evaluated through simulations to provide a consistent and globally optimized set.

Two key simulation/experiment benchmarks are proposed. First, the effectiveness of the recirculation strategy can be judged by comparing beam measurements at a similar linac configuration (such as JLab) to simulation results to ensure efficacy of the predicted recirculation performance from simulations. Second, the appropriateness of the at-energy bunch compression strategy can be evaluated by again comparing beam measurements with simulations at an extant facility such as Jlab or SLAC.

VI. CONCLUSION

Given an appropriate site and a reasonable provision for conventional construction, an FEL facility based on a recirculated SRF linac meeting the recent BESAC criteria [1] of “high repetition rate, ultra-bright, transform limited, femtosecond x-ray pulses over a broad photon energy range” can be achieved for a modest initial investment. Perhaps more importantly, the utilization of a recirculated SRF linac will provide a cost-effective opportunity for a scientifically significant, world-class FEL facility providing 25 keV photons possibly exceeding with its cw performance the scientific reach of the European XFEL.

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