

# VARIABLE GAP UNDULATOR FOR 1.5-48 KEV FREE ELECTRON LASER AT LINAC COHERENT LIGHT SOURCE\*

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## Abstract

We study the feasibility of generating femtosecond duration Free-Electron Laser with a variable photon energy from 1.5 to 48 keV, using an electron bunch with the same characteristics of the LINAC Coherent Light Source (LCLS) bunch, and a planar undulator with additional focusing. We assume that the electron bunch energy can be changed, and the undulator has a variable gap, allowing a variable undulator parameter. It is assumed to be operated in an ultra-low charge and ultra-short pulse regime.

## Introduction

The success of the LINAC Coherent Light Source (LCLS) [1] motivates an extension of the capacity, capabilities, and quality of this revolutionary new light source. Here, we study the possibility of generating hard x-ray FEL at LCLS with a wide tunable photon energy of 1.5 - 48 keV. A planar undulator with additional focusing is assumed. To achieve the wide tunable range, the electron beam energy is changed between 4.6 and 13.8 GeV, and the undulator, with a 2.5 cm period, variable gap is also varied accordingly to allow the undulator parameter to be changed to satisfy the resonant condition. Based on analytical calculation, we study the requirements on the electron bunch parameters and the FEL performance, optimizing the system parameters. Detailed numerical simulation using GENESIS [2] is done with the optimized parameter set.

## Electron Bunch Parameters

We explore the parameter space first with analytical scalings. We evaluate the characteristics of an X-ray FEL, like gain length, pulse duration, power, as a function of the radiation wavelength, beam energy, electron beam charge, and peak current, using Ming Xie code [3].

The normalized emittance scales like the cubic root of the charge, in the low charge regime, where the thermal emittance dominates. If the contributions from RF curvature and space charge cannot be neglected the transverse normalized emittance depends on charge as [4]:  $\varepsilon_N = 1.5 \times 10^{-6} (0.111 \times 10^6 Q^{2/3} + 0.18 \times 10^{12} Q^{4/3} + 0.18 \times 10^{24} Q^{8/3})^{1/2}$ , where  $Q$  is in units of Coulomb and  $\varepsilon_N$  in m-rad. With this scaling, the transverse normalized emittance as a function of electron bunch charge for low-charge region can be estimated. Here, we consider the case of  $Q = 10$  pC with  $\varepsilon_N = 0.11$  m-mrad.

Since the peak current and the bunch length depend on the photo-injector and bunch compression, the situation in this case is more complicated. We scale the bunch length at the photo-injector exit as the charge to the power  $1/3$  and assume also that we use velocity bunching. For the low-charge range in which we are interested, as mentioned above, the electron bunch rms length as a function of charge is assumed to be  $\sigma_L = 0.03Q^{1/3}$ , where  $\sigma_L$  is in units of meters and  $Q$  in Coulomb. Notice that, for  $Q = 10$  pC,  $\sigma_L \approx 6.5 \mu\text{m}$ , which gives a peak current <sup>1</sup> of  $I_{pk} = 185$  A. Here, we assume that we require the final peak current to be 2 kA after compression. For the case of  $Q = 10$  pC, the magnetic compression factor is about 11 with the initial peak current of about 185 A. Notice that for this case of  $Q = 10$  pC, the final  $I_{pk} = 2$  kA sets the electron bunch final rms length of  $0.6 \mu\text{m}$ , *i.e.*, rms temporal duration of 2 fs. This should make the final FEL approaching the single spike operation mode at  $\lambda_r = 1$  nm.

## FEL Performance

We briefly review the key physics parameters which we need to consider, before optimizing the system based on these considerations. The FEL parameter [5] is defined as  $\rho = (1/2\gamma_0) \{ (I_{pk}/I_A) [(K^2 [JJ]^2) / (2k_w^2 \sigma_x \sigma_y)] \}^{1/3}$  where  $\gamma_0 = [(1 + K^2/2)\lambda_w / (2\lambda_r)]^{1/2}$  is the Lorentz factor of the electron resonant energy with  $\lambda_r$  the resonant FEL radiation wavelength;  $K \approx 93.4 B_w \lambda_w$  where  $B_w$  is the undulator peak field in Teslas and  $\lambda_w$  the undulator period in meters;  $[JJ] = J_0[\xi] - J_1[\xi]$ , with  $\xi \equiv a_w^2 / [2(1 + a_w^2)]$  and  $a_w = K/\sqrt{2}$ ,  $J_0$  and  $J_1$  being the 0<sup>th</sup>-order and 1<sup>st</sup>-order Bessel functions;  $k_w = 2\pi/\lambda_w$ ;  $\sigma_{x(y)} = \sqrt{\varepsilon_N \beta_{x(y)} / \gamma_0}$  is the electron beam transverse  $x(y)$  rms size;  $I_{pk}$  is the peak current; and  $I_A \equiv 4\pi\epsilon_0 m c^3 / e \approx 17045$  Amp, the Alfvén current. With this FEL parameter  $\rho$ , which characterizes the coupling efficiency of the electron bunch and the FEL, the 1-D power gain length is readily defined as  $L_G^{1D} \equiv \lambda_w / (4\sqrt{3}\pi\rho)$ . We optimize the beta function assuming that an external focusing (*e.g.*, FODO cell lattice) is applied. It has been shown from rigorous analysis [6] that the FEL gain length can be expressed by a universal scaling function  $L_G^{1D}/L_G = F(\eta_d, \eta_\varepsilon, \eta_\delta)$ , where  $\eta_d = L_G^{1D}/Z_R$  characterizes the diffraction effect with  $Z_R = 4\pi\sigma_x^2/\lambda_r$  being the Rayleigh range;  $\eta_\varepsilon = (L_G^{1D}/\beta) [4\pi\varepsilon_N / (\gamma_0 \lambda_r)]$  characterizes the emittance effect; and  $\eta_\delta = 4\pi\sigma_\delta L_G^{1D}/\lambda_w$  characterizes the chromatic effect, where  $\delta = (\gamma - \gamma_0)/\gamma_0$  is the relative energy deviation. According to Ref. [3], the universal function  $F(\eta_d, \eta_\varepsilon, \eta_\delta)$  can be fitted into a 19-parameter function

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<sup>1</sup>The definition of the peak current is  $I_{pk} \equiv Qc/(\sqrt{2\pi}\sigma_L)$ , where  $c$  is the speed of light in vacuum.

$\eta$ , so that  $L_G^{1D}/L_G = 1/(1 + \eta)$ . The saturation power is fitted empirically as  $P_{sat} \approx 1.6\rho (L_G^{1D}/L_G)^2 \gamma_0 m_e c^2 I_{pk}$ .

For a SASE FEL, coherent spikes develop during the FEL process. The FWHM duration of the coherent spike is related to the FEL bandwidth [7]  $L_{spike}(z) = c\sqrt{\pi}/\sigma_\omega(z)$ , where  $\sigma_\omega(z) = \omega_r \sqrt{3\sqrt{3}\rho/(k_w z)}$ , is the FEL rms bandwidth as a function of the  $z$ -coordinate in the undulator. The total number of spikes is  $N_{spike} = \sigma_L/L_{spike}$ , for an electron bunch having a Gaussian temporal distribution with rms length of  $\sigma_L$ . Notice that, due to the highly non-linear dependence of the FEL gain on the current, for a temporal Gaussian distribution, the effective length is  $\sigma_L$ .

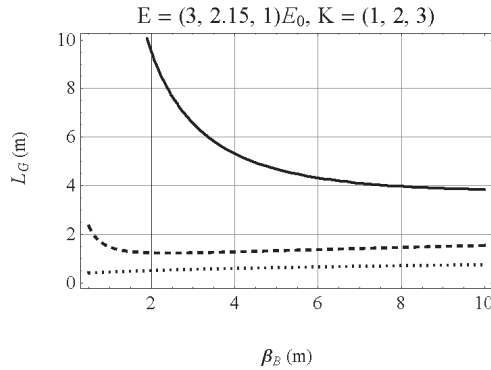


Figure 1: FEL gain length as a function of  $\beta$ -function for various  $E$  and  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

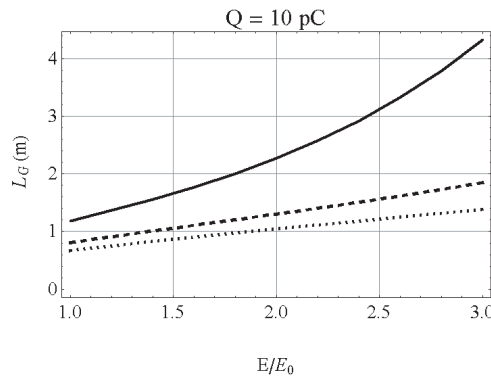


Figure 2: FEL gain length for fixed  $\beta_B = 6$  m, but with various  $E$  and  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

**Optimization** Here, we use the notation  $E_0 = 4.6$  GeV and the undulator period  $\lambda_w = 0.025$  m. We vary the electron energy  $E$  and the undulator parameter  $K$  to find a reasonable parameter set. We first find what is the optimum value of the focusing in the undulator. Since the gain length would be the longer for shorter wavelength, we optimize the focusing strength with emphasis on the short wavelength end. To do this we consider the case of the shortest wavelength, with  $K = 1$  and  $E = 13.8$  GeV, and

plot the gain length as a function of the focusing strength. This case corresponds to the FEL photon energy of 48 keV (FEL wavelength of  $\lambda_r = 0.26$  Å), and is shown as the solid curve in Fig. 1. In the same Fig. 1, we also show two other cases for FEL with photon energy of 1.5 keV (FEL wavelength of  $\lambda_r = 8.5$  Å) (dotted curve) and 12.4 keV (FEL wavelength of  $\lambda_r = 1.0$  Å) (dashed curve) as comparison. In the following calculations, we will choose  $\beta_B = 6$  m to cover all the cases.

For this chosen  $\beta_B = 6$  m, we plot in Fig. 2, the gain length as a function of energy for  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve). All the calculations are for charge  $Q = 10$  pC and with the final peak current of  $I_{pk} = 2$  kA. It is seen that for the shortest wavelength case, the gain length is slightly longer than 4 m.

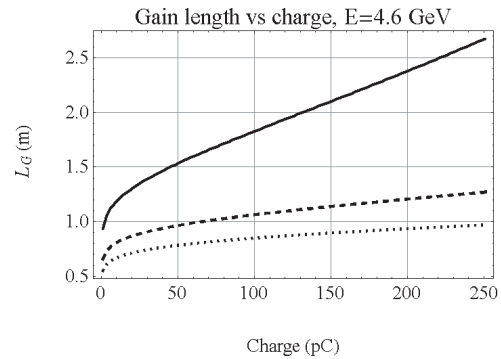


Figure 3: FEL gain length for fixed  $\beta_B = 6$  m and fixed energy  $E_0 = 4.6$  GeV, but with various charge  $Q$  and  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

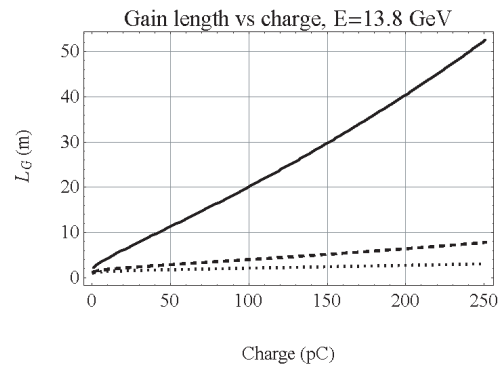


Figure 4: FEL gain length for fixed  $\beta_B = 6$  m and fixed energy  $E_0 = 13.8$  GeV, but with various charge  $Q$  and  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

In Fig. 3 we show the gain length as a function of electron bunch charge  $Q$  for  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve). The plot in Fig. 3 shows clearly that at minimum beam energy, corresponding to wavelength between 8 and 2 Å as  $K$  is decreased from 3 to 1, the gain length remains always within good values, less than 3 m. We repeat now the evaluation of the gain length as a function of charge at the maximum beam energy of

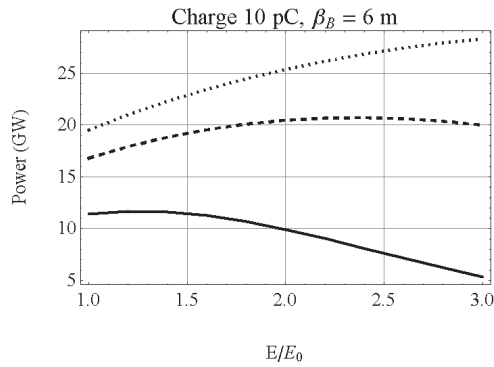


Figure 5: FEL saturation power for fixed  $\beta_B = 6$  m and fixed charge  $Q = 10$  pC, but with various  $E$  and  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

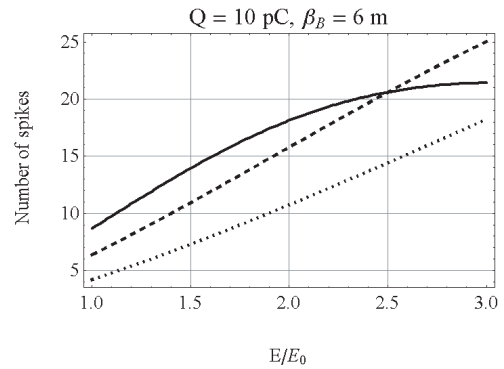


Figure 7: Coherent spikes # vs. beam energy for a fixed charge of 10 pC and various  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

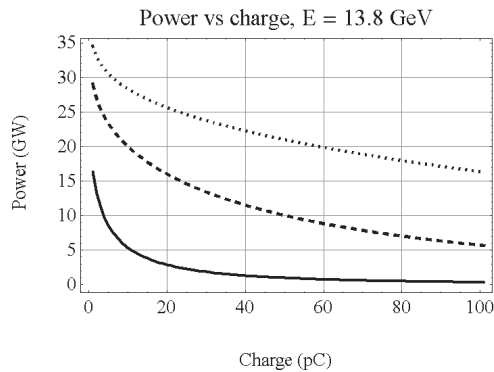


Figure 6: FEL saturation power for fixed  $\beta_B = 6$  m and fixed  $E = 13.8$  GeV, but with various charge  $Q$  and  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve).

$E = 13.8$  GeV. Figure 4 shows that at the maximum beam energy and  $K = 1$ , only small values of charge (up to 15 pC) can be used for a reasonably short gain length. The FEL saturation power as a function of  $E$  and  $K$  at a fixed charge of 10 pC is plotted in Fig. 5, which shows that with these parameters, the FEL peak power can always be larger than GW. For a more close look at the high energy end, we plot in Fig. 6, the FEL saturation power as a function of charge for various  $K = 1$  (solid curve), 2 (dashed curve), and 3 (dotted curve). Again, to get GW level FEL power, a charge as low as 15 pC is necessary for 48 keV FEL.

**Coherence** Due to the fact that the SASE FEL starts from shot-noise, the temporal coherence is developed purely due to the slippage of the photon over the electrons. For a fixed charge of 10 pC, to generate 1.5-48 keV FEL with various undulator parameter and electron energy, the coherent spike can be as long as a few tens of nm. For charge of 10 pC, and final peak current of  $I_{pk} = 2$  kA, the electron bunch length is on the order of  $1 \mu\text{m}$ . So, for the low energy FEL case, there will be a few to a few tens spikes in the pulse. This is shown in Fig. 7.

As a summary, in Table 1, we show two extreme cases: the low energy 1.5 keV and the high energy 48 keV FEL.

Table 1: Two Extreme Cases (1.5 keV and 48 keV FEL).

Parameter (Symbol)	1.5 keV	48 keV	Units
Electron energy ( $E$ )	4.599	13.797	GeV
FEL wavelength ( $\lambda_r$ )	8.488	0.257	Å
Pierce parameter ( $\rho$ )	2.23	0.58	$10^{-3}$
Gain length ( $L_G$ )	0.668	4.325	m
Saturation power ( $P_{sat}$ )	19.5	5.4	GW
Coherent photon # ( $N$ )	166.5	1.4	$10^9$
Spike length ( $L_{coop}$ )	142.6	27.6	nm
Spikes # ( $N_{spike}$ )	4.2	21.4	

### GENESIS Simulation

In above, we discussed the overall FEL performance using analytical formulae. Here, we choose three FEL cases, with 1.5, 12.4, and 48 keV FEL resonant energy, and evaluate in detail the FEL characteristics using GENESIS. In Table 2 we show the key parameters used in the simulation.

First we consider the 1.5 keV FEL case. In Fig. 8, we show the FEL power gain curve. It is seen that around 15 meters into the undulator, the FEL starts to saturate, with a saturation power around 20 GW. As expected, around saturation there are only a few spikes as in Fig. 9, where the

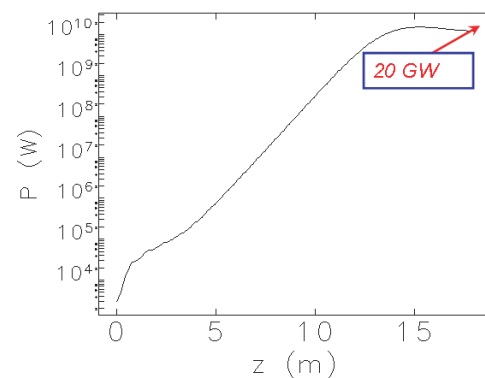


Figure 8: GENESIS simulation of the FEL power gain curve for the 1.5 keV FEL case.

Table 2: Parameters and Performance for the Three FEL Cases: 1.5, 12.4, and 48 keV FEL with GENESIS Simulation.

Parameter	Symbol	1.5 keV FEL	12.4 keV FEL	48 keV FEL	Units
Electron bunch centroid energy	$E$	4.6	9.9	13.8	GeV
Electron bunch slice relative energy spread	$\sigma_\delta$	1.0	0.46	0.33	$10^{-4}$
FEL wavelength	$\lambda_r$	8.5	1.0	0.26	$\text{\AA}$
FEL power $e$ -folding length	$L_G$	0.8	1.2	3.0	m
FEL saturation power	$P_{sat}$	20	20	5	GW
Number of photon per pulse	$N$	20	5.3	0.3	$10^{10}$

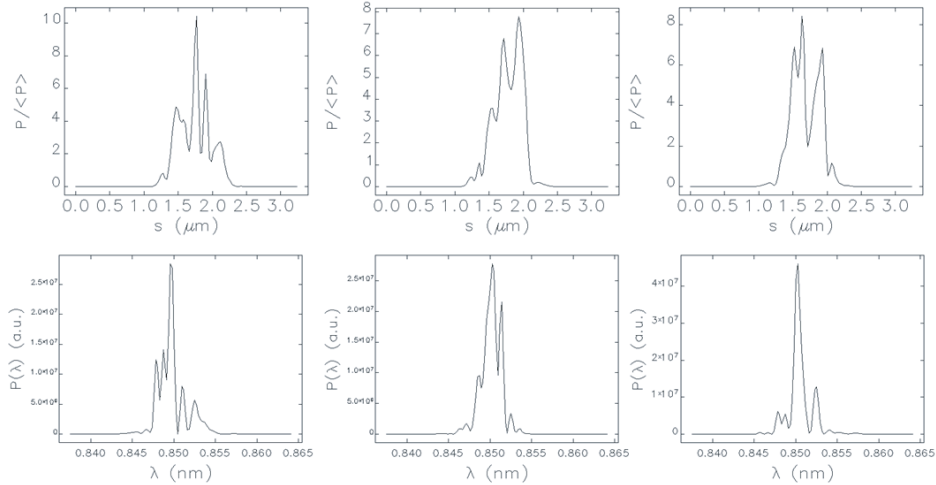


Figure 9: GENESIS simulation of the FEL (1.5 keV) pulse at 15 m into the undulator showing just a few spikes.

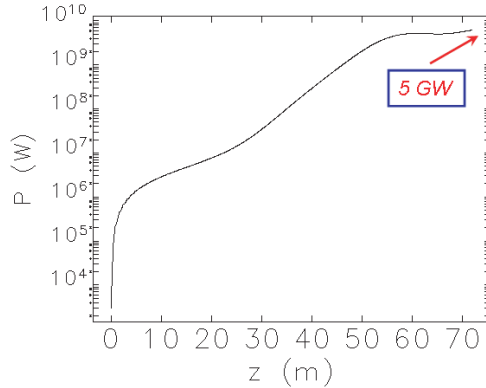


Figure 10: GENESIS simulation of the FEL power gain curve for the 48 keV FEL case.

FEL pulse temporal profile and spectrum are taken at 15 meters into the undulator. With three different initial random seeds, the final FEL pulse contains a few spikes as in the upper row of Fig. 9. The corresponding spectrum for each case is shown as the lower row in Fig. 9. The results for the 48 keV case are in Fig. 10 showing a saturation length of about 55 m and a saturation power of 5 GW.

### Conclusions

We study the feasibility of a tunable, short pulse, X-ray FEL with photon energy from 1.5 to 48 keV, using an elec-

tron beam like the one in the LCLS and a 2.5 cm period, variable gap, planar undulator. The beam energy changes from 4.6 to 13.8 GeV, the electron charge is kept at 10 pC, and the undulator parameter varies from 1 to 3. The undulator length needed to saturate the 48 keV FEL is about 55 m, with a peak power around 5 GW. At longer wavelength the saturation length is as short as 15 m, and the peak power around 20 GW. The results from the analytical models and the GENESIS simulations show that the system is feasible. The large wavelength range, full tunability and short, few femtosecond pulses, together with the large peak power, would provide a powerful research tool.

### REFERENCES

- [1] P. Emma *et al.*, Nature Photonics, 2010 (published online: 1 Aug 2010 — DOI: 10.1038/NPHOTON.2010.176).
- [2] S. Reiche, NIMA **429**, 243 (1999).
- [3] M. Xie, PAC95, p. 183, 1995.
- [4] J.B. Rosenzweig and E. Colby, in AIP Conf. Proc. Vol. **335**, p. 724 (1995).
- [5] R. Bonifacio, C. Pellegrini, and L.M. Narducci, Opt. Commun., **50**, 373 (1984).
- [6] L.-H. Yu *et al.*, Phys. Rev. Lett., **64**, 3011 (1990); Y.H. Chin *et al.*, Phys. Rev. A **46**, 6662 (1992).
- [7] E.L. Saldin *et al.*, Opt. Commun., **148**, 383 (1998).