# OPTIMIZATION OF A SOFT X-RAY SASE-FEL PARAMETERS AT POHANG ACCELERATOR LABORATORY

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*Abstract*

A free-electron laser (FEL) based on self-amplified spontaneous emission has been designed. This FEL is utilizing the existing 2.5 GeV electron linear accelerator at Pohang Accelerator Laboratory (PAL). The radiation wavelength was chosen to be in the water-window region 3-4 nm which can be used for biological imaging. In this paper, it is shown that the PAL is particularly suited for this wavelength if the existing linear accelerator is employed without having major modification. For 4 nm wavelength, the saturated power is shown to be approximately 5 GW with a saturation length of about 30 m.

## INTRODUCTION

Several free-electron lasers (FELs) based on self-amplified spontaneous emission (SASE) are under study, construction or operation around the world including LCLS, TTF, SCSS, LEUTL, VISA, etc. Among these, the Linac Coherent Light Source (LCLS) at Stanford Linear Accelerator Center (SLAC) in USA and the TTF project at DESY in Germany are under construction and aiming at producing hard x-rays with 1.5 Å and 1.0 Å wavelength, respectively. Recently, there is an increasing demand in these facilities to have a capability of producing soft x-ray radiation as well, 20-50 Å wavelength region. One of the promising applications in this wavelength is x-ray microscopic imaging in the water-window region (23-44 Å), especially the imaging of biological specimens in their natural state. Due to large absorption differences between carbon and oxygen in the water-window region, the natural contrast between protein and water can be attained. In addition, due to short pulse nature of the radiation of the order of 100 femto second, a single-pulse exposure measurements can be carried out to obtain images of living cells before the specimen changes in its structure caused by radiation damage.

The SASE principle is based on the FEL amplifier where the initial spontaneous radiation near the undulator entrance is used as input electromagnetic (EM) wave. This co-propagating EM wave combined with the undulator field generates a beat (i.e. ponderomotive) wave whose phase velocity is slower than the speed of light and can be synchronized with electrons. Depending on the relative phase with respect to the beat wave electrons can lose or gain energy, causing micro-bunching of the electron beam of the order of the wavelength of the EM wave. The electrons in the micro-bunch then acts coherently to produce an exponential growth of the radiation intensity which is proportional to the square of the number of electrons at saturation. This SASE principle has been successfully demonstrated recently at UCSB, LEUTL at Argonne National Laboratory (ANL) [1] and at DESY [2].

The wavelength of the output radiation through an undulator is given by

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1 + a_U^2 + \gamma^2\theta^2\right), \tag{1}$$

where $\lambda_U$ is the undulator period, $\gamma$ is the ratio between the electron energy and the electron rest energy 0.511 MeV, $a_U = K$ for helical and $a_U = \frac{K}{\sqrt{2}}$ for planar undulator. Here, $K$ is the undulator parameter given by $K = \frac{eB_U\lambda_U}{2\pi m_0 c}$ with $B_U$ the peak magnetic field on the mid-plane of the undulator, $m_0$ the electron rest mass, $e$ and $c$ the electron charge and speed of light respectively. In Eq. (1), $\theta$ is the angle between the undulator mid-plane and the observation position. The equation shows that the radiation wavelength is inversely proportional to the beam energy squared. Eq. (1) also shows that higher magnetic field (i.e., smaller undulator gap) gives longer wavelength and this is due to the fact that higher magnetic field reduces the magnitude of the longitudinal velocity of an electron beam.

Currently at the PAL, a 2.5 GeV electron linear accelerator (or linac) is used to inject electrons into the 2.5 GeV storage ring. The circulating electron beam in the storage ring then emits synchrotron radiation during the curved motion through bending magnets and insertion devices with a lifetime of 20 hours at maximum beam current 170 mA. Normally beam is injected two times per day and time required for injection is less than 10 minutes. Thus the linac is in stand-by mode for most of the time.

The electron energy of 2.5 GeV is particularly suited for soft x-ray generation with a FEL. This paper concerns a soft x-ray FEL using the PAL injector linac. First, we introduce the parameter optimization of the soft x-ray. For comparison purpose we consider two different energies of an electron beam, 2.5 GeV and 3 GeV respectively. We then show some characteristic feature of the FEL. Time-independent and -dependent numerical simulation results are depicted.

## SOFT X-RAY FEL PARAMETERS

The amplification of the EM wave is due to the collective instability of an electron beam. The instability produces an exponential growth of the EM field intensity and of the bunching given by the bunching parameter:

$$B = \frac{1}{N_e}\sum_{k=1}^{N_e} \exp\left(\frac{2\pi i z_k}{\lambda}\right) \tag{2}$$

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where $z_k$ is the longitudinal position of the $k^{th}$ electron with respect to the bunch center, $N_e$ is the total number of electrons and $i = \sqrt{-1}$. The growth saturates when the bunching parameter is of the order of one. In one-dimensional approximation the power growth before saturation is given by

$$P \approx \frac{1}{9} P_n \exp\left(\frac{z}{L_{g,1d}}\right) < P_{sat}, \tag{3}$$

where $L_{g,1d} \approx \frac{\lambda_U}{4\sqrt{3}\pi\rho}$ is the one-dimensional gain length and $P_n$ is the effective input-noise power proportional to the square of the initial bunching parameter $|B_0|^2$ and it is the power for spontaneous coherent undulator radiation of length $L_g$. $P_n$ is proportional to the inverse of the number of electrons in a coherence length (i.e. $P_n \sim \frac{\rho^2 c E_e}{\lambda}$). In the case of SASE FEL, the saturation occurs approximately after 20 gain lengths. The FEL performance is mainly described by the FEL parameter $\rho$ which is given by

$$\rho = \frac{1}{\gamma}\left(JJ(\chi)\frac{a_U}{4}\frac{\omega_p}{\omega_U}\right)^{2/3}, \tag{4}$$

where $\omega_U = \frac{2\pi c}{\lambda_U}$ and $\omega_p$ is the plasma frequency given by $\sqrt{\frac{n_e e^2}{\epsilon_0 m_0}}$. Here $n_e$ is the electron density and $\epsilon_0$ is the free-space permeability. Note that the FEL parameter $\rho$ is proportional to $n_e^{1/3}$. The function $JJ(\chi)$ is given by

$$JJ(\chi) = \begin{cases} 1 & : \text{ helical undulator} \\ J_0(\chi) - J_1(\chi) & : \text{ planar undulator,} \end{cases}$$

where $\chi = \frac{K^2}{4(1+K^2/2)}$ and $J_n$ is the $n^{th}$-order Bessel function. The radiated energy at saturation is roughly $\rho N_e E_e$, where $N_e$ is the total number of electrons. The number of emitted photons per electron at saturation is then given by $N_\gamma = \rho\frac{E_e}{E_\gamma}$, where $E_\gamma$ is the photon energy. The significance of the FEL parameter $\rho$ can be summarized as

- Saturation length $L_{sat} \sim \frac{\lambda_U}{\rho}$
- Radiation power at saturation $P_{sat} \sim \rho P_{beam}$
- Frequency bandwidth $\frac{\Delta\omega}{\omega} \sim \rho$,

where $P_{beam}$ is the peak power of the electron beam, $P_{beam} = E_e I_p$ with $I_p$ the peak current. Therefore high peak current is desired to obtain high power at saturation. In Figs. 2 and 3 we have not taken into account the undulator segments which will increase the saturation length as in the case of Fig. 1.

In order for the collective instability to be developed the following three conditions should be met:

- Electron beam emittance must match the diffraction-limited emittance: $\epsilon < \frac{\lambda}{4\pi}$
- Beam energy spread must be smaller than the FEL parameter: $\frac{\sigma_\gamma}{\gamma} < \rho$
- Gain length must be shorter than the Rayleigh length: $L_g < Z_R = \frac{2\pi\sigma_x^2}{\lambda}$, where $\sigma_x$ is the rms size of the radiation.

When three-dimensional effect is considered, the FEL-gain length can be expressed by introducing a universal scaling function [3]

$$L_g = L_{g,1d}\left(1 + \eta(\eta_d, \eta_\epsilon, \eta_\gamma)\right), \tag{5}$$

where

$$\begin{aligned} \eta_d &= \frac{L_{g,1d}}{2k\sigma_x^2} = \frac{L_{g,1d}}{Z_R} \\ \eta_\epsilon &= \left(\frac{L_{g,1d}}{\beta}\right)\left(\frac{4\pi\epsilon}{\lambda}\right) \\ \eta_\gamma &= 4\pi\left(\frac{L_{g,1d}}{\lambda_u}\right)\left(\frac{\sigma_\gamma}{\gamma}\right). \end{aligned} \tag{6}$$

In the above equations, $\eta_d$ is the diffraction parameter, $\eta_\epsilon$ is the angular spread parameter, and $\eta_\gamma$ is the energy spread parameter. These scaling parameters measure the deviation of the beam from ideal case. M. Xie fitted $\eta$ numerically with 19 fitting parameters and listed the fitting coefficients which will be omitted here [3]. The saturated power obtained empirically by fitting results is given by

$$P_{sat} \approx 1.6\rho\left(\frac{L_{g,1d}}{L_g}\right)^2 P_{beam}. \tag{7}$$

Table I shows the major beam and FEL parameters for 4 nm at PAL. It is seen that the undulator-gap height is 0.85 cm and the period is 3.3 cm. A moderate gap height was chosen to prevent possible deterioration of the beam quality from wake field and surface roughness. For planar undulator with Nd-Fe-B hybrid permanent magnet, the peak magnetic field in the mid-plane is given by [4]

$$B_U[T] = 0.95 \times 3.44 \exp\left[-5.08\frac{g}{\lambda_U} + 1.54\left(\frac{g}{\lambda_U}\right)^2\right]$$
$$0.1 < \frac{g}{\lambda_U} < 1.0$$

where $g$ is the full gap of the undulator. This gives the peak magnetic field on the mid-plane of 1.03 T and as a result the undulator parameter $K$ is 3.173 as Table I shows.

## RESULTS

In order to obtain saturation power as a function of the length, the GENESIS program was invoked, which is a three-dimensional simulation code for a SASE FEL. This program has a capability of numerically integrating the equations of motion in time-independent or time-dependent mode. Fig. 1 shows the power as a function of the undulator length. It is seen that the saturated power is approximately 5 GW and the saturation occurs at around 30

Table 1: Parameters of the 4 nm FEL.

| Parameter | |
|---|---|
| Radiation wavelength, $\lambda$ (nm) | 4 |
| Electron beam energy, $E_e$ (GeV) | 2.5 |
| Undulator period, $\lambda_U$ (cm) | 3.3 |
| Undulator full gap, $g$ (mm) | 8.5 |
| Undulator peak field in the mid-plane, $B_U$ (T) | 1.03 |
| Undulator parameter, $K$ | 3.173 |
| Normalized rms beam emittance, $\epsilon_n$ ($\mu$rad) | 2.0 |
| Peak electron beam current, $I_p$ (kA) | 3.0 |
| Rms energy spread, $\sigma_\gamma/\gamma$ | $6.01\times10^{-4}$ |
| Gain length (3-D), $L_g$ (m) | 1.146 |
| FEL parameter (3-D), $\rho$ | $1.32\times10^{-3}$ |
| FWHM bunch length, $\tau_B$ (fs) | 231 |
| Gain correction factor, $\eta$ | $\sim$0.11 |
| Saturation length, $L_{sat}$ (m) | $\sim 30$ |
| Saturation power, $P_{sat}$ (GW) | $\sim 5$ |

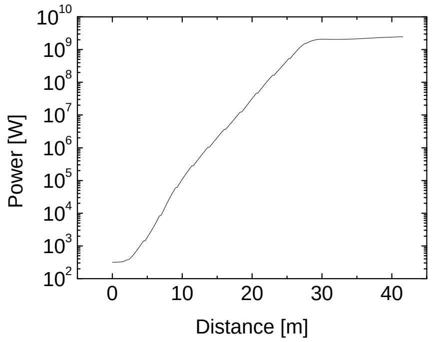


Figure 1: Power as a function of the undulator length for 4 nm FEL. Undulators are assumed to be segmented.

m. Figs. 2 and 3 show the saturation power and the saturation length as functions of the normalized emittance and the peak electron beam current. These figures were obtained assuming undulators were not segmented so that power and saturation length were slightly different from the segmented case. The saturation power increases as the normalized emittance decreases and the peak beam current increases. On the other hand the saturation length decreases as the normalized emittance decreases and the peak beam current increases. The natural emittance of 2 mm mrad and the peak beam current of 3 kA have been chosen in view of the reasonable performance of a rf photocathode electron gun.

To find the focusing requirement and therefore the optimal $\beta$ functions, both the natural undulator focusing and quadrupole focusing by FODO structure were considered. It is well know that the planar undulator gives a vertical

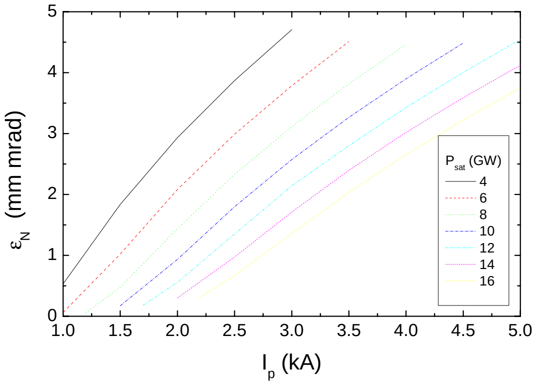


Figure 2: Saturation power as functions of the normalized emittance and peak beam current.

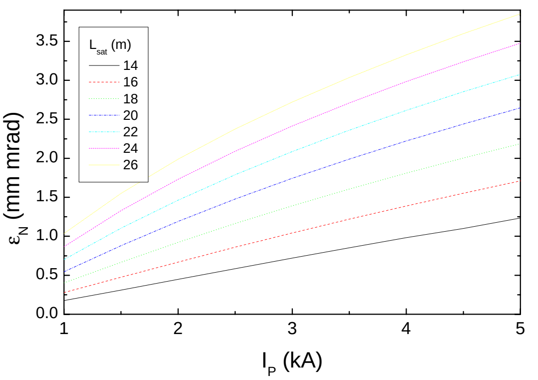


Figure 3: Saturation length as functions of the normalized emittance and peak beam current.

focusing due to edge effect of the magnet blocks and the equation of motion is given by

$$\frac{d^2y}{dz^2} + \frac{1}{2\rho^2}y = 0,$$

where $z$ runs along the longitudinal axis of the undulator. The vertical transfer matrix due to a planar undulator is therefore

$$M_y = \begin{pmatrix} \cos(\frac{L}{\sqrt{2}\rho}) & \sqrt{2}\rho\sin(\frac{L}{\sqrt{2}\rho}) \\ -\frac{1}{\sqrt{2}\rho}\sin(\frac{L}{\sqrt{2}\rho}) & \cos(\frac{L}{\sqrt{2}\rho}) \end{pmatrix}, \qquad (8)$$

where $L$ is the straight length of the undulator and $\rho$ is the radius of curvature on the axis where the magnetic field is peak.

To allow the space for quadrupole magnets and diagnostic instruments such as beam position monitors undulators are split. The space requirement between undulator sections is such that the phase slip of the electron bunch behind the electromagnetic wave is integer multiple of the radiation wavelength: $(c-v)t = n\lambda$ where $v$ is the electron speed $n$ is an integer, and $t$ is the gap-traversal time of the electron. Therefore, for $n = 1$,

$$L \approx \lambda_u \left(1 + \frac{K^2}{2}\right). \tag{9}$$

This yields $L = 19.916$ cm.

Fig. 4 shows the horizontal and vertical $\beta$ functions as a function of the straight length. It is seen that average $\beta$ function is about 4 m. Fig. 5 shows the saturation power

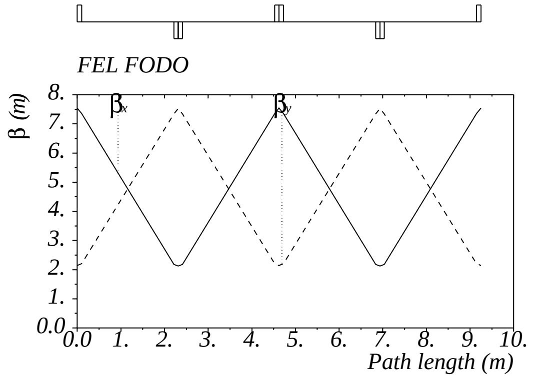


Figure 4: $\beta$ function along the undulator and FODO focusing structure.

and the saturation length as a function of the average $\beta$ function. This figure indicates that the chosen 4 m average $\beta$ value is reasonably optimized to yield high saturation power and low saturation length.

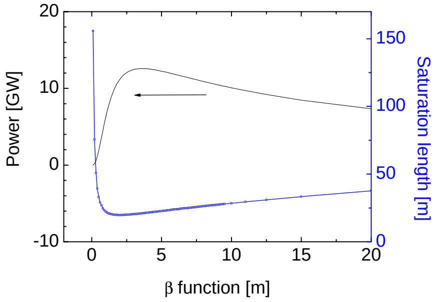


Figure 5: Saturation power and saturation length as a function of the average $\beta$ function along the undulator.

Finally, effect of the wakefield due to the undulator vacuum chamber has been considered. In highly relativistic approximation, the longitudinal wakefield due to a resistive wall effect from a single electron is given by

$$W_z(s) = -\frac{4cZ_0}{\pi a^2}\left(\frac{1}{3}e^{-s/s_0}\cos\frac{\sqrt{3}s}{s_0} - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{x^2 e^{-x^2 s/s_0}}{x^6+8}dx\right), \tag{10}$$

for $s > 0$ and $W_z(s) = 0$ for $s < 0$, where $s$ is along the longitudinal position of the test particle with respect to the particle generating field, $Z_0 = 120\pi\ \Omega$, $s_0 = (2a^2/Z_0\sigma)^{1/3}$, $\sigma$ is the conductivity of the chamber material, and $a$ is the pipe radius. Table 1 shows that the full gap height of the undulator was chosen to be 8.5 mm. Assuming 0.5 mm thickness of the vacuum chamber, Fig. 6 shows that the saturation power decreases about a factor of 2 when copper chamber was assumed.

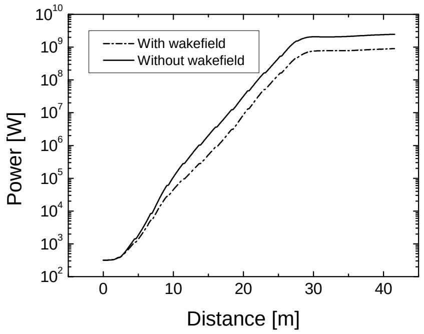


Figure 6: Power as a function of the undulator length with (dashed) and without (solid) wakefield in the undulator. Copper chamber with radius 3.75 mm was assumed.

## CONCLUSION

In the paper we have described the SASE FEL to produce the soft x-ray. It is seen that with the present 2.5 GeV rf linear accelerator at the Pohang Accelerator Laboratory, the radiation of 4 nm wavelength can be produced with reasonable saturation power and the saturation length. The wavelength are decreased to 3 nm if the electron energy is increased to 3 GeV. Currently a design study is in progress which includes the start to end simulation. More details of this work is reported in these proceedings [5].

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