A 0.1 nm SASE FEL AT POHANG ACCELERATOR LABORATORY

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Abstract

Parameters for a newly proposed 0.1 nm SASE FEL at the Pohang Accelerator Laboratory are described. This new facility features that in-vacuum undulators of 5.3 mm gap are employed in conjunction with an S-band rf linear accelerator to produce a 10.053 GeV electron beam. When a 1 nC electron beam with 1.1 mm mrad normalized slice emittance and 0.015% relative slice energy spread enters the undulator, output radiation power of 5 GW is expected in approximately 94 m saturation length. Linac beam dynamics study has been performed and supported that the chosen design parameters are achievable. Effect of wakefields on the FEL performance is also considered and shown to be insignificant.

INTROCUTION

Starting with the 0.15 nm Linac Coherent Light Source (LCLS) [1] at Stanford Linear Accelerator Center (SLAC) which is expected to be completed its commissioning in 2009, hard X-ray free electron lasers (FELs) of 0.1 - 0.15 nm wavelength range are now coming into stage. Following the LCLS, the 0.1 nm SPring-8 Compact SASE Source (SCSS) [3] in Japan is aiming at the completion by 2011 and the 0.1 nm European XFEL facility [2] at DESY in Germany is planning to be completed by 2012.

In this paper, we describe basic design parameters of a new 0.1 nm SASE FEL at the Pohang Accelerator Laboratory (PAL). Among several possible options, we choose a layout which consists of a conventional normal conducting S-band rf linear accelerator (hereafter linac) followed by an in-vacuum undulator of a 5.3 mm gap which is comparable with the vacuum-chamber gap of an out-vacuum undulator such as the one employed for LCLS at SLAC. The S-band rf linac when it is combined with the energy doubler can provide a maximum 27 MV/m accelerating gradient if a 60 MW klystron drives two accelerating sections ($E \approx 20\alpha\sqrt{P/2}$ where E is the energy gain in MeV, P is the klystron power in megawatt unit and α is the energy-gain factor due to the energy doubler). As a result the total length of the linac becomes approximately 550 m.

The in-vacuum undulator has been adopted because it can reduce the effective gap height, thereby reducing the saturation length as well as increasing the peak power. As a result, the electron energy of 10 GeV with 1.1 mm mrad normalized beam-slice emittance and 1 nC bunch charge in 100 fs bunch duration is expected to generate an approximately 5 GW peak power with 94 m saturation length.

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In this paper we briefly introduce basic parameters of a 0.1 nm SASE FEL at PAL. Although this facility will also be capable of delivering longer wavelengths, here we focus on the shortest wavelength only because it is at this wavelength that the requirement for electron beam and undulator parameters are most demanding. First, parameters based on the simplified theory will be presented. These parameters will then be verified with the help of a computer program. Estimated sensitivities of the peak power and the saturation length on various electron and undulator parameters are also described. Finally, a summary and conclusion is provided.

PARAMETERS

As mentioned a configuration consisting of a normal conducting 10.053 GeV S-band linac combined with in-vacuum undulators was chosen for the PAL FEL. Details of the linac layout and beam dynamics simulation can be found in these proceedings [4]. Also the photocathode rf gun together with the injector linac is described in a separate paper [5]. Table I shows the major beam and FEL parameters for 0.1 nm at PAL. The gap height 5.3 cm was chosen to prevent possible deterioration of the beam quality due to wakefields from resistive wall, surface roughness and others. For planar undulator of Nd-Fe-B hybrid permanent magnet, the peak magnetic field in the mid-plane is given by [6]

$$B_u[T] \approx 3.44 \exp\left[-5.08\frac{g}{\lambda_u} + 1.54\left(\frac{g}{\lambda_u}\right)^2\right], \quad 0.1 < \frac{g}{\lambda_u} < 1.0$$

where g is the full gap of the undulator. This gives the peak magnetic field on the mid-plane of 1.0659 T for $\lambda_u = 2.23$ cm and $g = 5.3$ mm. As a result the undulator parameter K is 2.2201 as Table I shows.

NUMERICAL RESULTS

Peak power and saturation length

In order to obtain saturation power as a function of the length, the GENESIS [7] 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 evolution of the peak radiation power as a function of the electron beam path along the undulator. In this figure, a number of breaks between the undulators have

Table 1: Parameters of the 0.1 nm FEL derived from three dimensional theory

Parameter	
Radiation wavelength, λ (nm)	0.1
Electron beam energy, E_e (GeV)	10.053
Undulator type	In-vacuum
Undulator period, λ_u (cm)	2.23
Undulator full gap, g (mm)	5.3
Undulator peak field in the mid-plane, B_u (T)	1.0659
Undulator parameter, K	2.2201
Normalized rms beam slice emittance, ϵ_n (μrad)	1.1
Peak electron beam current, I_p (kA)	3.4
Bunch charge, Q (nC)	1.0
Rms slice energy spread, σ_γ/γ	1.53×10^{-4}
Average β function (m)	$\sim$22
Gain length (3-D), L_g (m)	5
FEL parameter (3-D), ρ	3.64×10^{-4}
FWHM bunch length, τ_B (fs)	231
Saturation length, L_{sat} (m)	94
Saturation power, P_{sat} (GW)	5

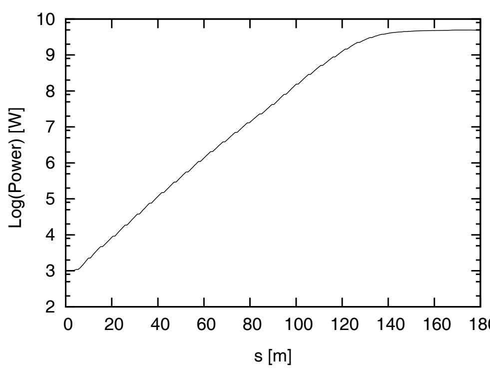

Figure 1: Evolution of the peak power along the the undulator with the initial beam parameters being given by Table 1

been inserted to allow the space for quadrupoles, beam position monitors and other radiation diagnostics. Without breaks the saturation power and length are well in agreement with the estimation in Table 1.

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 normalized emittance of 1.1 mm mrad and the peak beam current of 3.4 kA have been chosen in view of the reasonable performance of a rf photocathode electron gun.

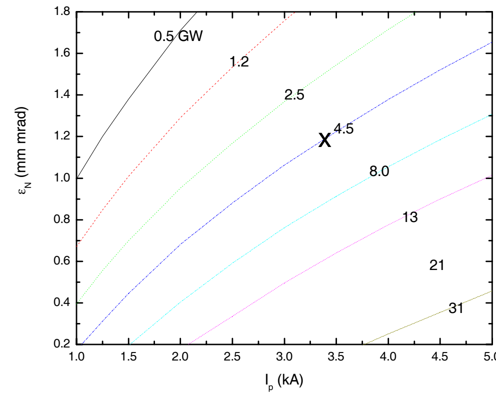

Figure 2: Dependence of the peak power on the normalized emittance and the peak power for 0.1 nm PAL xFEL. The cross mark indicates the operating point

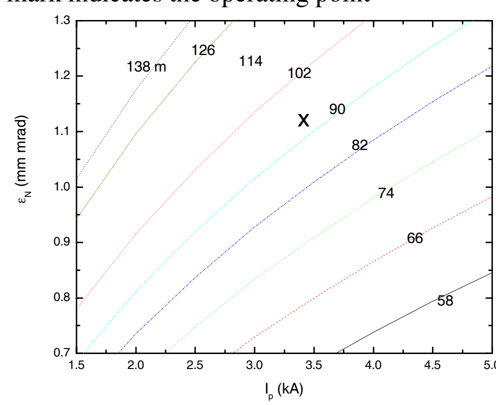

Figure 3: Dependence of the peak length on the normalized emittance and the peak power for 0.1 nm PAL xFEL. The cross mark indicates the operating point

Undulator Optics

Use of in-vacuum undulators requires transition sections on both sides of an undulator and therefore overall length of the FEL tends to be longer. Tentatively, a space of approximately 45 cm has been placed between undulators allowing a space to install a quadrupole combined with correctors, beam position monitors and monitor. The length of undulator is 4.014 m. Fig. 4 shows the horizontal and vertical β functions as a function of the straight length. It is seen that average β function is about 22 m.

Fig. 5 shows the saturation power and the saturation length as a function of the average β function. This figure shows that the chosen 22 m average β value is reasonably optimized to yield high saturation power and low saturation length. The quadrupole gradient is approximately 20 T/m with 10 cm in length.

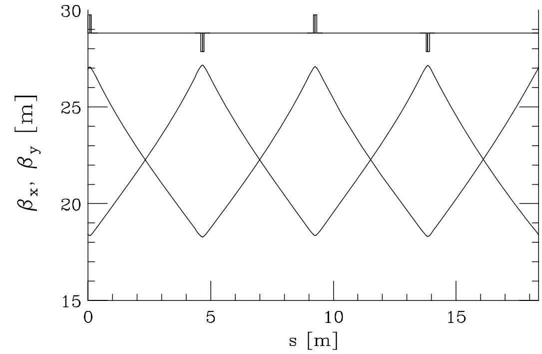

Figure 4: β functions inside the undulator

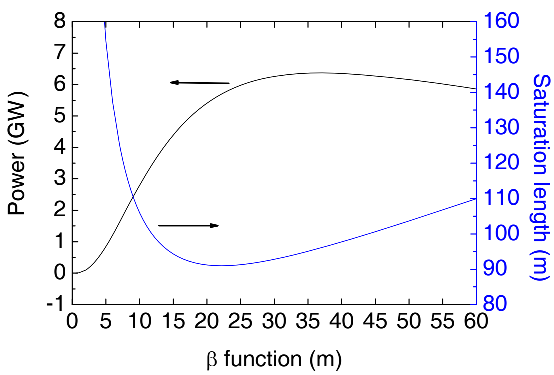

Figure 5: Power and saturation length as a function of the average β function

Sensitivities to undulator and electron beam parameters

The next important question to be addressed is the sensitivities of radiation power and the saturation length to various electron beam related parameters, focusing parameters and undulator parameters. While this kind of study has to be carried out with the help of a computer program, it will be instructive to examine it first based on the FEL theory. The results are summarized in Table 2.

The large values associated with the undulator related parameters ($\Delta\lambda_u$ and ΔK) are not significant. For example, 10 micron systematic error in the undulator period length yields 3.2×10^{-5} relative power deviation.

EFFECT OF WAKEFIELDS

For in-vacuum undulator, shielding plates are needed to minimize the wakefields induced by a beam. Owing to the resistive nature of the shielding material, electrons still induce wakefields both transversely and longitudinally. Only the induced energy spread over the bunch is important to consider because other effects such as the transverse kick and the average energy loss can be cured by employing beam-based alignment and tapering of the undulator. Although the geometry of the shielding plate resembles a parallel-plate chamber, it is well-known that wakefields due to circular chamber is more severe than than the parallel-plate chamber [8]. So we consider here the circular-chamber geometry considering a safety margin. It is also known that when frequency-dependent conductivity is considered, the aluminum chamber is preferable to the copper chamber.

Table 2: Sensitivities of the saturation power and length to 0.1 nm PAL FEL parameters at saturation

Saturation power sensitivity	Saturation length sensitivity
$\frac{\Delta P_{sat}/P_{sat}}{\Delta\lambda_u/\lambda_u}$ = 7.3	$\frac{\Delta L_{sat}/L_{sat}}{\Delta\lambda_u/\lambda_u}$ = -3.1
$\frac{\Delta P_{sat}/P_{sat}}{\Delta K/K}$ = 2.4	$\frac{\Delta L_{sat}/L_{sat}}{\Delta K/K}$ = -1.4
$\frac{\Delta P_{sat}/P_{sat}}{\Delta\beta/\beta}$ = 0.5	$\frac{\Delta L_{sat}/L_{sat}}{\Delta\beta/\beta}$ = 0.0
$\frac{\Delta P_{sat}/P_{sat}}{\Delta\gamma/\gamma}$ = -0.6	$\frac{\Delta L_{sat}/L_{sat}}{\Delta\gamma/\gamma}$ = 1.4
$\frac{\Delta P_{sat}/P_{sat}}{\Delta\sigma_\gamma/\sigma_\gamma}$ = -0.4	$\frac{\Delta L_{sat}/L_{sat}}{\Delta\sigma_\gamma/\sigma_\gamma}$ = 0.2
$\frac{\Delta P_{sat}/P_{sat}}{\Delta\epsilon_n/\epsilon_n}$ = -1.7	$\frac{\Delta L_{sat}/L_{sat}}{\Delta\epsilon_n/\epsilon_n}$ = 1.1
$\frac{\Delta P_{sat}/P_{sat}}{\Delta I_p/I_p}$ = 1.9	$\frac{\Delta L_{sat}/L_{sat}}{\Delta I_p/I_p}$ = -0.6

In highly relativistic approximation, the longitudinal wakefield due to a resistive wall effect from a single electron is given by

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

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, $Z_0 = 120\pi\ \Omega$, $s_0 = (2a^2/Z_0\sigma_{ac})^{1/3}$ with σ_{ac} being the ac conductivity of the chamber material ($\sigma_{ac} = \sigma_{dc}/(1 - i\omega\tau)$, and a is the pipe radius. Here τ is the relaxation time. Fig. 6 shows the energy change per unit length over the bunch length at the entrance of the undulator when circular Cu chamber of 2.5 mm radius is assumed. The two curves correspond to the dc (blue) and ac (red) conductivity cases respectively. Fig. 7 is for Al vessel case. It is seen from these figures that Al vessel has an advantage over the Cu vessel. Assuming 100 m long Al undulator, the energy spread over the useful beam is approximately 0.1% which is acceptable.

It is expected that the power and saturation length will be changed when the wakefields are taken into account. Fig. 8 shows the power evolution. This figure shows that for Al case the power decrease is approximately 20%.

Wakefields due to the surface roughness have also been considered. In this case, the aspect ratio $AR = \lambda_s/h$ of the surface roughness is an important parameter where λ_s

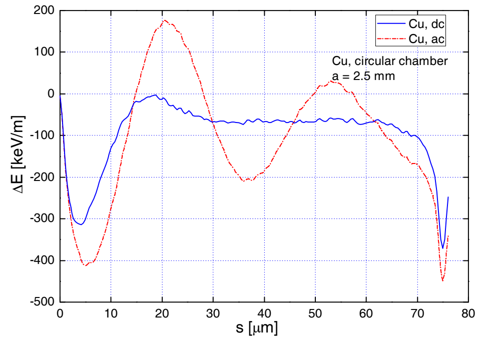

Figure 6: Energy change per unit length over the bunch length for circular Cu vessel of 2.5 mm radius for dc (blue) and ac (red) conductivities respectively

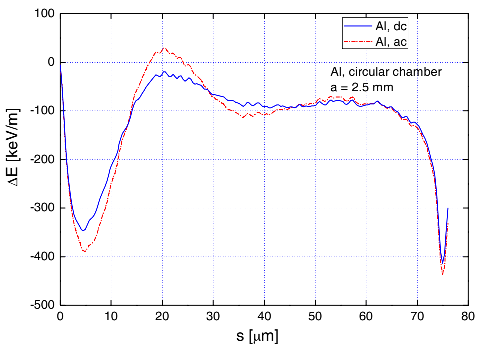

Figure 7: Energy change per unit length over the bunch length for circular Al vessel of 2.5 mm radius for dc (blue) and ac (red) conductivities respectively

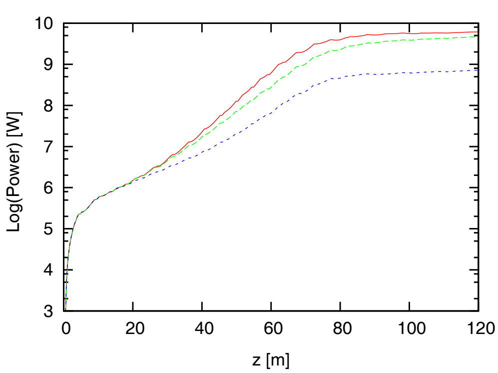

Figure 8: Power as a function of the undulator length without (red) wakefield, with wakefields for circular Al vessel of 2.5 mm radius (green) and circular Cu vessel 2.5 mm cases (blue)

is the period and h is the depth of the roughness. From our study, whose details is not described here it has been found that $AR > 300$ would not affect the FEL performance.

CONCLUSION

In the paper we have described the SASE FEL to produce a 0.1 nm X-ray. With a 10 GeV rf linear accelerator, the radiation of 0.1 nm wavelength can be produced with 5 GW saturation power in 92 m saturation length when 1 nC electron bunch of 1.1 mm mrad and 0.015% relative energy spread enters the undulator.

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