DESIGN CONSIDERATIONS FOR SASE-FEL AT PLS

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Abstract

The infrared (IR) free-electron laser (FEL) which is in design stage at Pohang Light Source is a self-amplified spontaneous emission (SASE) system that is driven by a 60 MeV to 100 MeV test linac facility. We present results of the numerical simulation for the design of the IR SASE-FEL at the PLS. It is shown that high-gain SASE-FEL with 1.5 μm radiation wavelength is driven by a 61 MeV electron beam from the S-band rf linac and a about 5 m long undulator. The generation of third harmonic from bunching at the fundamental wavelength is also investigated as a purpose toward enhancing the usefulness of the IR SASE-FEL facility at the PLS. In this paper, we investigate sensitivity of the beam parameters, emittance, energy spread, beam energy and peak beam current, to the performance of the designed IR SASE-FEL by a simulation code GINGER. We also investigate the influence of beam parameters on the bunching of fundamental and nonlinear third harmonic, and show that the third harmonic emission results in the same trend as that of the fundamental.

INTRODUCTION

SASE is driven by the random longitudinal bunching on an electron beam that is traversing along the undulator[1,2]. The fundamental radiation wavelength is determined by parameters of the electron beam energy and the strength of the undulator. A method to obtain shorter wavelengths at given beam energy is to utilize coherent bunching at higher harmonics. It may be generated by nonlinear harmonic bunching in the exponential gain regime starting from either SASE or a weak input signal[3,4].

Pohang Light Source (PLS) is designing a SASE-FEL system by using a test linac facility. The system is based on an existing electron linac that consists of a thermionic RF gun, an alpha magnet for bunch compression, and two S-band linac sections to provide electron energies from 60 MeV to 100 MeV. In this paper, we investigate the sensitivity of emittance, energy spread, beam energy and peak beam current to the performance of the designed IR SASE-FEL. Achievable values for the normalized emittance and the peak beam current are considered as boundaries for the design of the system. The design study is centered to achieve saturation at the radiation wavelength of 1.5 μm. For this design, we consider a 5 m long undulator with a period length of 15 mm and peak magnetic field value of 1.37 T.

It was known that for radiation emission, odd harmonics are favored as they couple effectively to the natural undulating motion of the electron beam through a linearly polarized undulator. It was shown that nonlinear harmonic bunching and radiation could serve as a seed for further FEL amplification at the regions such as x-ray (LCLS), (LEUTL and VISA) and far-infrared (ISIR) [5,6]. In particular, we investigate characteristics of third harmonic in the our designed SASE-FEL system because it may be a promising way to produce radiation power at the regime of shorter wavelength. It is shown in our simulation that the third harmonic experience silimar trend in gain and saturation similar to the fundamental. One purpose of this paper will be to predict the usefulness of the third harmonic output in the our IR SASE-FEL. A numerical simulation code is used to investigate the influence of electron beam parameters (i.e., emittance, energy spread, beam energy and peak beam current) on the field energy at the fundamental, and on the bunching of the fundamental and third harmonic, by using basic parameters corresponding to the SASE-FEL at the PLS.

CODE DESCRIPTION

A simulation study for the IR SASE-FEL at the PLS is carried out using the time-dependent code GINGER[7]. The main parameters of the electron beam and the undulator are given in Table I. GINGER is a direct descendent of the FEL code FRED which modeled the interaction between particles in one pondermotive well and a monochromatic, r- and z-dependent electromagnetic wave. The electron beam is modeled by discrete slices, each containing numerous macroparticles, to simulate the particle distribution in one ponderomotive well. GINGER also uses a moderate number of macroparticles (512-8192) per slice to represent the actual electrons in each beam slice. The equations of motion are averaged over an undulator period following the standard Kroll-Morton-Rosenbluth formulation while an eikonal approximation in time and space is used for field propagation. For nonwaveguide simulations, GINGER used an expanding radial grid whose spacing is approximately constant near the origin but grows exponentially near the outer boundary. For polychromatic SASE simulations, GINGER can be initiated with either electron beam shot noise or, alternatively, photon noise.

SIMULATON

In simulations with the time dependent GINGER code, we have chosen an electron beam with a parabolic distribution in longitudinal direction and with a Gaussian distribution in the transverse direction. We use 2048 macroparticles per slice and 60 slices to represent an electron beam in the simulation. For simplicity, we adopted a single-segment planar undulator with curved pole-face focusing.

We also injected an input power of 1 μW at the fundamental. GINGER calculates the output radiation energy at the fundamental, and beam bunching at both the fundamental and third harmonic. For this analysis, we first compare the longitudinal locations of saturation of the output field energy and the fundamental bunching. It is shown that peak in the bunching occurs at almost the same position with the output field energy saturates. Note that the third harmonic does saturate at the same position where the fundamental saturates.

Table 1: Basic IR SASE-FEL Parameters at the PLS.

Electron beam energy	61.3 MeV
Normalized beam emittance	5 mm mrad
Peak beam current	300 A
Beam energy spread	0.1 %
Radiation wavelength	1.5 μm
Undulator period	15 mm
FEL parameter	0.0046
Peak undulator magnetic field	1.37 T
Power gain length	17.8 cm
Undulator parameter	1.918

Emittance scans

For the emittance sensitivity scans, the normalized emittance was varied between 1 mm mrad and 10 mm mrad, which results in the saturation distance approximately doubling. Figure 1 shows the field energy as a function of undulator distance versus beam emittance at the fundamental wavelength. The field energies for smaller emittances than 6 mm mrad show saturation in smaller distance than about 5 m long undulator. The field energies for larger emittances than 6 mm mrad show slow increases of the field energy up to the 15 m long undulator. Larger emittances requires much longer saturation lengths and shows decreased outputs, even though the FEL operation is kept. Over this limited range, the field energy at the fundamental shows significant sensitivity to emittance.

Energy spread scans

For the energy spread scans, the initial beam energy spread was varied between 1 % and 0.001 %. Figure 2 shows the field energy versus energy spread at the fundamental. For the energy spreads smaller than 0.1%, the field energies saturate in smaller distance than 5 m long undulator. For the energy spreads larger than 0.5%, the field energies do not show peak value up to 15 m long undulator.

Peak beam current scans

For the beam current scans, the peak beam current was varied between 200 A and 1000 A. Figure 3 shows the field energy at the fundamental versus the peak beam current. For peak beam currents larger than 300 A, the field energies show saturation in smaller distance than 5 m long undulator. For the peak beam current of 200 A, the field energy shows trend of increasing up to 15 m long undulator. Over this limited range, the field energy at the fundamental shows significant sensitivity to peak beam current.

Electron beam energy scans

For the electron beam energy scans, the beam energy was varied between γ=120 and γ=200. Figure 4 shows the field energy at the fundamental versus beam energy. Over this limited range, the field energy does not show significant sensitivity to the beam energy.

Performance of the IR SASE-FEL at PLS test linac facility

For the nominal parameters that are given in Table I, the simulation results show that saturation can be reached at about 4.5 m long undulator, as shown in Figure 5(a). The peak bunchings at the fundamental and the third harmonic also occur at about 4.5 m, as shown in Figure 5(b). Figure 5(b) shows the ratio of the bunching fraction of the third harmonic to fundamental is about 15% at 4.5 m long undulator. From these simulation results, we note that an undulator of a length of about 5 m is required to achieve saturation in the designed IR SASE-FEL.

In a one-dimensional model, the FEL parameter ρ is given by[16]

$$\rho = [\frac{I\gamma\Lambda^2}{I_A 16\pi^2\sigma^2}\frac{K^2}{(1+K^2/2)}(J_o(\xi)-J_1(\xi))^2]^{1/3}, \quad (1)$$

where I is the peak beam current, I_A=17,045 A is the Alfvên, $J_{0,1}$ are Bessel functions, and σ is the rms beam size. ξ= $\frac{K^2}{2(1+K^2)}$, where K is the undulator parameter. Under the nominal designed parameters, the FEL parameter is given by 0.0046.

The gain in the SASE-FEL can be estimated. Defining the gain as $G = E/E_o$ where E is the total energy when the saturation occurs and E_o is the energy at the first gain length, we calculate a gain, $G \simeq 1.0 \times 10^7$. The gain length in one-dimensional model is given by $L_G = \lambda_u/4\sqrt{3}\pi\rho$ where λ_u is fundamental radiation wavelength and the calculated gain length is given by 0.15 m. The three-dimensional gain length obtained from the numerical simulation was 0.17 m, which is good agreement with the one-dimensioanl calculated one.

CONCLUSIONS

In this paper, we presented the results of numerical simulation for the design of the IR SASE-FEL at the PLS. The FEL will be a 1.5 μm SASE system that is driven 61 MeV electron beam from S-band linac and a about 5 m long undulator. We have examined the influence of electron

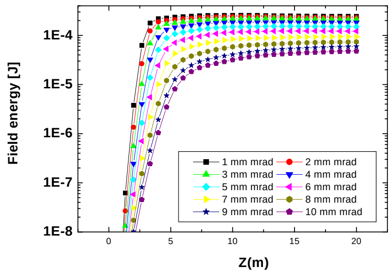

Figure 1: shows the field energy at the fundamental versus beam emittance as a function of the distance.

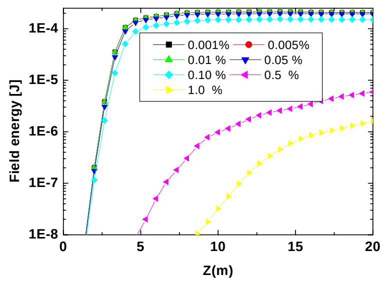

Figure 2: shows the field energy at the fundamental versus energy spread as a function of the distance.

beam parameters on performance of the high-gain SASE-FEL by using a numerical simulation code GINGER. We have also investigated the sensitivities of the radiation output energy to variations in beam emittance, energy spread, beam energy and peak current centered around the nominal designed parameters for IR SASE-FEL at the PLS. It is shown that the nonlinear third harmonic generation in the designed IR SASE-FEL at the PLS can be used to achieve shorter wavelengths and characteristics of its growth and saturation vary along with the fundamental. Since the nonlinear third harmonic is driven by the growth of the fundamental wavelength, the sensitivity of the nonlinear third harmonic to the beam parameters is shown to be comparable to that of the fundamental. That is, if the bunching is sufficient at the fundamental, the bunching for the third harmonic will also be sufficient.

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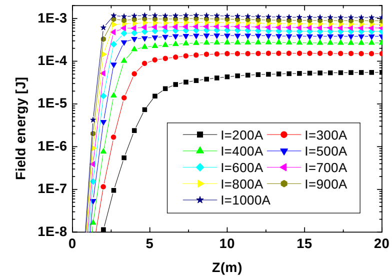

Figure 3: shows the field energy at the fundamental versus beam current as a function of the distance.

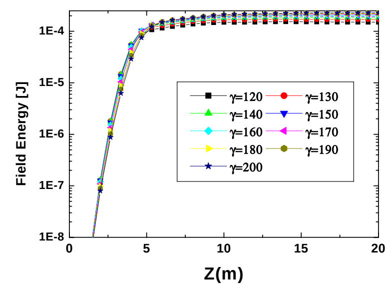

Figure 4: shows the field energy at the fundamental versus beam energy as a function of the distance.

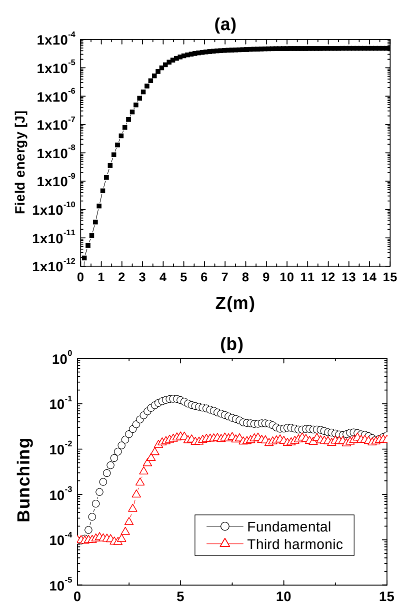

Figure 5: (a) shows the field energy at the fundamental. (b) shows the bunching fraction for the fundamental and third harmonic.