Emission of SASE-FEL in the in the Infrared Region and Measurement of its Characteristics

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Abstract

We are conducting experiments of Self-Amplified Spontaneous Emission (SASE) in the far-infrared region using a single-bunch beam from the L-band linac at ISIR, Osaka University. Characteristics of the electron beam were measured and it was found that the one-dimensional theory of SASE was applicable to our SASE experiments. We observed strong light emitted when the single-bunch electron beam passed through the wiggler. The intensity of light was measured as a function of the K-value of the wiggler and it increased by three orders of magnitude as the K-value increased. The intensity variation with the K-value agrees quite well with the SASE theory and it was concluded that we observed SASE in the infrared region

1 Introduction

The single-pass and high-gain Free Electron Laser (FEL) based on Self-Amplified Spontaneous Emission (SASE) has attracted attention as a strong candidate for realizing an X-ray laser and there are some proposals to construct such facilities using linear accelerators [1, 2]. A SASE-FEL in the short wavelength region necessitates a high intensity and high quality electron beam and a long wiggler. Theoretical and simulation studies have been extensively conducted on SASE, while only a limited number of experimental studies have been performed in the infrared region.

The 38 MeV, L-band linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University is equipped with a three-stage subharmonic buncher (SHB) system to produce a high-intensity single-bunch beam with charge up to 73 nC. Such a high intensity beam makes it possible to produce SASE in the infrared region. We have been developing an infrared FEL using the linac. In the course of developing the FEL, SASE was observed in 1991 at 20 and 40 μm wavelengths using a wiggler for the FEL and the single-bunch beam from the linac [3].

We recently began to study SASE-FEL again using the existing FEL system and the linac. First, characteristics of the single-bunch electron beam were measured and then expected performance of SASE-FEL was estimated using simple analytic formulas and the measured beam parameters. We are now conducting experiments to produce SASE and to measure characteristics of the radiation. In this paper, we report the recent progress of the SASE-FEL study at ISIR, Osaka University.

2 Experiment

The linac and the FEL system are shown schematically in Fig. 1. The electron beam with a peak current of 14 A and a duration of 5 ns is injected from a thermoionic cathode (YU-156) with an area of 3 cm^2 to the SHB system. After being compressed to a single bunch in the SHB system, the electron beam is accelerated with the 1.3 GHz linac to an energy of 11-32 MeV. The single-bunch electron beam is led to the FEL system through the achromatic beam transport line comprising two bending magnets and a quadrupole triplet in between them. It is focused at the center of the wiggler using a quadrupole doublet, and after passing through the wiggler it is stopped at the beam dump. The wiggler is a 32-period, planar wiggler of the horizontal oscillation type with the period length of 6 cm. The K-value can be varied over the range from 0.013 to 1.472.

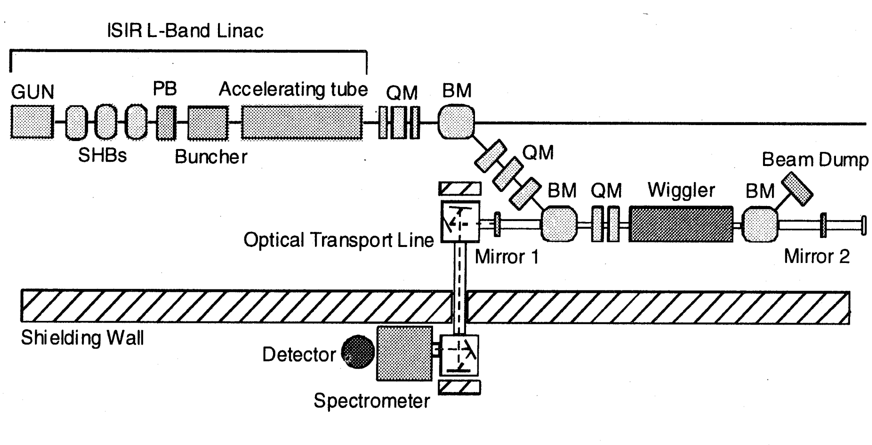

Fig. 1. Schematic layout of the ISIR L-band linac and the FEL system.

Characteristics of the electron beam were measured at a location 0.5 m downstream from the bending magnet in the straight beam line. The bunch length was obtained by measuring optical transition radiation, emitted when the electron beam passed through a stainless steal plate, using a streak camera with time resolution of shorter than 2 ps. The emittance of the electron beam was measured by the quadrupole scan method. The electron beam size was measured as a function of the focusing strength of the central quadrupole in the triplet at the exit of the linac, using a 0.1 mm thick fluorescent plate and a TV camera. The signal from the camera was processed using a personal computer with a video capture board, and the beam size was derived. The energy spectrum of the electron beam was measured using a momentum analyzer magnet located downstream in the straight line. The total charge in the single bunch beam, after passing through the wiggler, was measured at the beam dump with a Faraday cup.

In SASE experiments, the upstream mirror M1 shown in Fig. 1 was removed and the downstream mirror M2 was replaced with another spherical mirror with a different radius, so that light emitted toward the exit of the wiggler is efficiently transported through the evacuated optical transport line to the measurement room. The grating monochromator has not been used for spectral analysis of SASE light yet. Instead, the grating was replaced with a plane mirror and the spectrometer worked as a part of the optical transport line. Light passing through a window made of single-crystal quartz at the exit of the monochromator was detected with a liquid-helium-cooled Ge:Ga photoconductive detector. The detector has the time resolution of approximately 170 ns (FWHM). The signal from the detector was processed with a digital oscilloscope connected to a personal computer.

3 Experimental results and discussions

Characteristics of the single-bunch electron beam were measured over the energy range from 32 down to 11 MeV. They are listed in Table 1, together with the main parameters of the wiggler. The normalized emittance ε_N is approximately 200 π mm mrad and the relative energy spread is 1.1-4 %, depending on the electron energy. A typical energy spectrum of the electron beam is shown in Fig. 2. Charge in a single bunch was measured to be 22-38 nC. The peak current calculated from the charge per bunch and the measured bunch length of 20 ps exceeds 1 kA.

Table 1
Main parameters of the electron beam and the wiggler.

electron beam	
energy	11-32 MeV
energy spread (FWHM)	1.1-4 %
charge per bunch	22-38 nC
bunch length	20 ps
norm. emittance	150-250 π mm mrad
peak current	1 kA
mode	single bunch
acceleration frequency	1.3 GHz
repetition	60 Hz
wiggler	
total length	1.92 m
magetic period	60 mm
No. of periods	32
magnet gap	120-30 mm
peak field	0.37 T
K-value	0.013-1.472

According to the one dimensional theory of SASE [4], the power of coherent light grows exponentially as $P_{SASE} \propto \exp[z/L_{gain}]$, where z is the longitudinal distance along the wiggler and L_{gain} is the power gain length. It is given by $L_{gain} = \lambda_w/4\sqrt{3}\,\pi\rho$, where ρ is the FEL parameter. The one-dimensional formula is applicable when the following conditions are fulfilled; (a) $\varepsilon_{x\ \mathrm{or}\ y} < \lambda/4\pi$, (b) $L_{gain} < L_R$, and (c) $\sigma_\gamma/\gamma < \rho$, where $\varepsilon_{x\ \mathrm{or}\ y}$ is the horizontal or the vertical emittance of the electron beam, λ the wavelength of SASE, L_R the Rayleigh length, and σ_γ/γ the energy spread of the electron beam.

The condition (a) states that the transverse cross section of the electron beam should be included in that of the photon beam and it is tested in Fig. 3. The solid circles and the solid triangles are measured emittance of the electron beam. The curves with the K-values show $\lambda/4\pi$ calculated for three different K-values of the wiggler. The dash-dot line shows the beam emittance calculated for the normalized emittance of 200 π nm rad. The inequality is satisfied for the larger K-value below 20 MeV. The condition (b) states that light should be amplified before it spreads out due to diffraction. Substituting $L_R = 4\pi\varepsilon\beta/\lambda$ into the inequality (b), one obtains the inequality to be compared directly with experiment as $\lambda L_{gain}/4\pi\beta < \varepsilon$, where β is the betatron function. It is tested in Fig. 4. The solid circles and the solid triangles are the measured emittance and the curves show the left side of the inequality for three K-values. The condition (b) is apparently fulfilled. The condition (c) states that the energy spread of the electron beam should be less than the bandwidth of saturated light, which is equal to the FEL parameter ρ, and tested in Fig. 5. The solid circles are the measured energy spread and the curves show

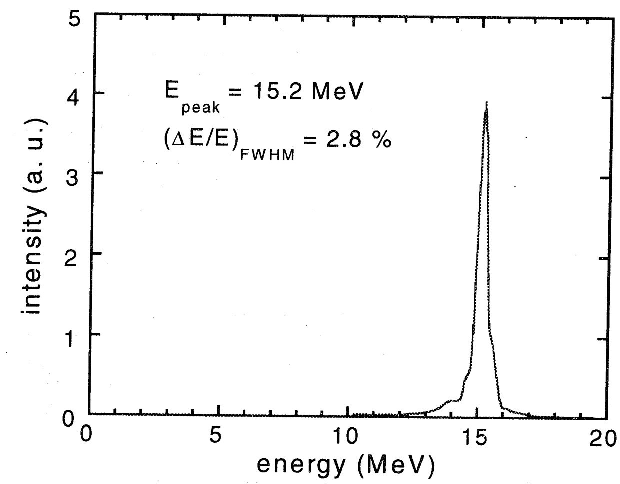

Fig 2. Energy spectrum of the electron beam.

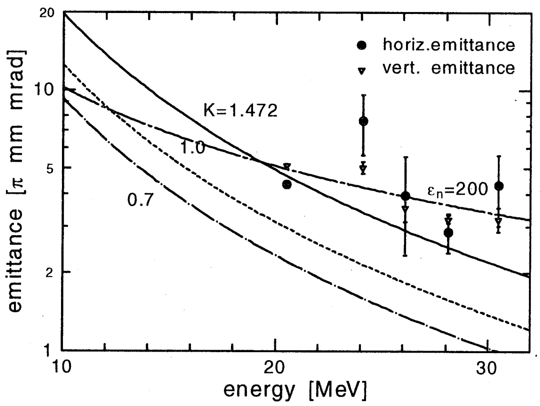

Fig 3. Measured emittance of the electron beam and the condition (a). See text for details.

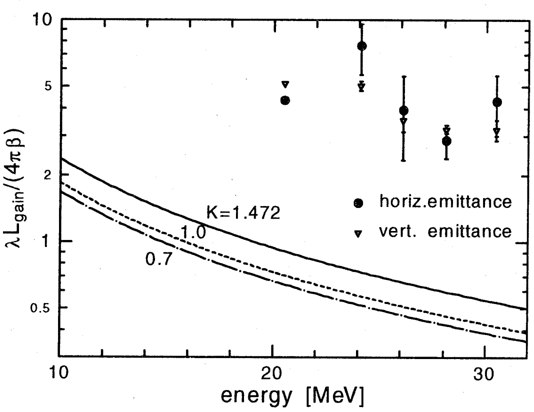

Fig 4. Measured beam emittance and the condition (b). See text for details.

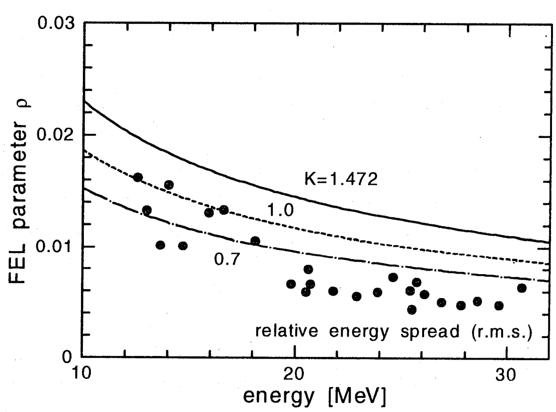

Fig 5. Measured energy spread of the electron beam and the condition (c). See text for details.

calculated FEL parameters for different K values. It can be seen that the inequality is satisfied for the larger K value in the entire energy region shown in Fig. 5. As a conclusion, most of the conditions are fulfilled in our experimental conditions, which means that the one-dimensional model is applicable to our SASE experiments. The maximum gain calculated using the theory exceeds 1×10^5 at an electron energy of 15 MeV and the K-value of 1.472.

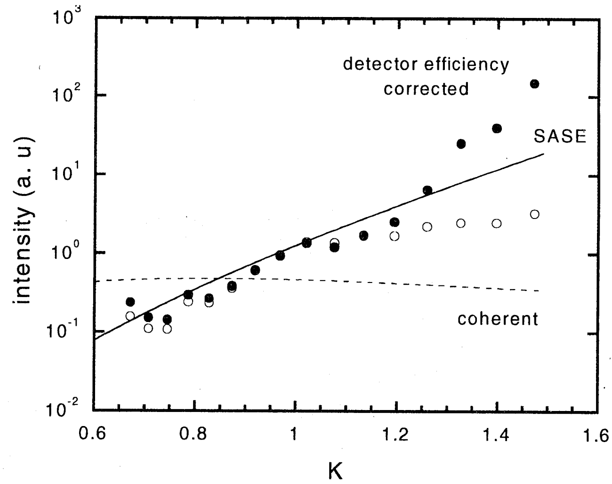

Fig 6. Light intensity as a function of the K-value of the wiggler. See text for details.

We conducted experiments to observe SASE at electron beam energies lower than 15 MeV and larger K values of the wiggler, because gain is expected to be higher and the one-dimensional conditions are fulfilled. We have observed the strong light emitted by the single bunch beam when passing through the wiggler. Figure 6 shows the light intensity measured as a function of the K value of the wiggler. The electron energy was 12.6 MeV and the energy spread was 3.8 %. The charge in a bunch was 18.2 nC. The K value was varied from 0.67 to 1.47 and then the wavelength changed from 72 to 157 μm. The open circles are intensities measured with the detector. Since the sensitivity of the detector changes considerably in the above wavelength region, the measured intensities are corrected using the spectral sensitivity of the detector and the intensities after correction are shown with the solid circles in Fig. 6. The intensity of light increases by three orders of magnitude for the K-value ranging from 0.67 to 1.47. The solid curve shows a fit of the SASE theory, where the normalization factor of the formula is adjusted to fit the experimental data. The agreement between the theory and experiment is excellent. The dotted line in Fig.6 is the calculated intensity of incoherent or coherent synchrotron radiation from the wiggler. The functional dependence of the light intensity on the K-value is quite different from that of SASE. Therefore it is concluded that we have observed SASE in the infrared region.

References

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