ANALYSIS OF INTENSITY FLUCTUATIONS OF SASE USING THE AR MODEL

R. Kato#, S. Kashiwagi, S. Isaka, C. Okamoto, T. Yamamoto, S. Suemine, G. Isoyama,
ISIR, Osaka University, Mihogaoka, Ibaraki, Osaka 567-0047, Japan

H. Sakaki,
J-PARC, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki 319-1195, Japan

Abstract

Using the auto-regressive model analysis, we have analyzed the intensity fluctuation of the SASE produced with the L-band linac and the FEL system at the Institute of Scientific and Industrial Research, Osaka University. It has been found that the fluctuation of the SASE intensity is affected by the beam current in the frequency region less than 0.1 Hz and that the contribution ratio of the beam current to the intensity fluctuation of SASE is evaluated to be 18 % in the period longer than 100 seconds.

INTRODUCTION

We are conducting experimental studies on Self-Amplified Spontaneous Emission (SASE) in the infrared region using the L-band linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University [1-3]. The intensity of SASE fluctuates intrinsically because the number of coherent optical pulses generated in an electron bunch changes statistically. In the actual system, however, another factor producing intensity fluctuations also shows up, namely instability of the linac. Generally speaking, it is difficult to distinguish contributions of these two factors in measured intensity fluctuations. We have applied the auto-regressive (AR) model, which is one of the techniques of statistical analysis and has been successfully applied to analysis of instability of rf linacs [4,5], to evaluate the contribution of beam instability in the measured data. In the AR model, the present data can be expressed with a linear combination of the past data plus white noise. By using the AR model analysis, contribution ratios of the beam fluctuations to the intrinsic fluctuations of SASE in measured data can be evaluated. In this paper, we will report results of the analysis of intensity fluctuations of SASE measured at ISIR, Osaka University, using the AR model.

LINAC AND MEASUREMENT SYSTEM

The L-band linac is equipped with a three-stage sub-harmonic buncher (SHB) system composed of two 1/12 and one 1/6 SHBs in order to produce an intense single-bunch beam with charge up to 91 nC/bunch. For the single-bunch operation mode, the electron beam with a peak current up to 28 A (typically 18 A in our experiments) and a duration of 5 ns is injected from a thermionic gun (EIMAC, YU-156) into the SHB system. After being compressed to a single-bunch, the electron beam is accelerated to 11 - 32 MeV in the 1.3 GHz accelerating tube. The electron beam is transported via an achromatic beam transport line to the wiggler for the FEL system. It is the 32 period planar wiggler with the period length of 60 mm. The K-value can be varied from 0.01 to 1.47. The main characteristics of the electron beam and the wiggler are listed in Table 1. Light emitted by the single-bunch beam passing through the wiggler was reflected with a downstream mirror, and led to the measurement room via a 10 m long optical transport line, which was evacuated with a rotary pump. The high vacuum in the beam transport line and the low vacuum in the optical transport line were separated by a 0.2 mm thick, 20 mm in diameter synthetic diamond window. The optical light was detected with a Ge:Ga photoconductive detector cooled with liquid-helium.

We measured the SASE intensity over a period of approximately 12 minutes with an interval of 0.73 s, together with the beam current measured at the entrance of the wiggler. The measured data are shown in Figure 1. The SASE intensity shown by the red lines in the lower part of the figure contains higher frequency components due to the intrinsic fluctuations of SASE, as well as the long-period variations, which are similar to those of the beam current shown by the blue lines in the upper part of the figure.

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

Electron beam	
Accelerating frequency	1.3 GHz
Energy	12.8 MeV
Energy spread (FWHM)	1.97 %
Charge/bunch	10-20 nC
Bunch length	20-30 ps
Peak current	0.5 – 1.0 kA
Normalized emittance	150-200 π mm mrad
Repetition	60 Hz
Mode	Single-bunch
Wiggler	
Total length	1.92 m
Magnetic period	60 mm
No. of periods	32
Magnet gap	120-30 mm
Peak field	0.37 T
K-value	0.013-1.472

#kato@sanken.osaka-u.ac.jp

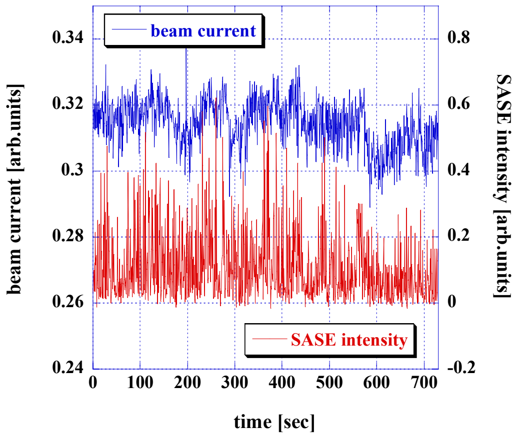

Figure 1: Beam current measured at the entrance of the wiggler (upper) and the SASE intensity (lower) over a period of approximately 12 minutes with an interval of 0.73 s.

AR MODEL

The AR model is a method for time series analysis [6]. It may be applicable to analysis of the feedback structure in a complicated system consisting of mutually interacting elements. For the AR model analysis of the feedback system with two parameters, the present data *X(n)* can be expressed by the linear combination of the past data *X(n-m)*, *Y(n-m)* and the white noise $e_x(n)$:

$$\begin{bmatrix} X(n) \\ Y(n) \end{bmatrix} = \sum_{m=1}^{M} \begin{bmatrix} a_{xx}(m) & a_{xy}(m) \\ a_{yx}(m) & a_{yy}(m) \end{bmatrix} \cdot \begin{bmatrix} X(n-m) \\ Y(n-m) \end{bmatrix} + \begin{bmatrix} e_x(n) \\ e_y(n) \end{bmatrix}, \quad (1)$$

where M is a regressive number. The optimum regressive number M is derived with FPE (Final prediction error)[7] or AIC (Akaike information criterion) [8]. Fitting the eq. (1) to a set of time series data, we obtain the factor a_{ij} and the noise e_i. These factors and noises show the feedback system modelled on the computer.

Assuming that the noises $e_x(n)$ and $e_y(n)$ are equal to zero, the system will either converge or diverge. When an impulse noise is applied to the feedback system in the stationary state without noise, it will attenuate soon for the stable system. By analysing the impulse response of the system, it is possible to know how the perturbation propagates with time among the components, and whether the system is stable or not. This method is called “impulse response analysis” and gives a physical image of the feedback structure in the time domain. Although a delta function impulse is applied to a component, its response is not like the delta function, but has a tail, since the component is influenced by its own past values and the other components.

The power spectrum is defined as the Fourier transform of an auto-covariance of the fluctuation data. Fractional factors of the influences due to the each intrinsic noise power contributing to the power spectrum are called the noise power contribution ratios. By analyzing the noise power contribution ratios, we can know which is the most influential component in the system.

ANALYSIS WITH THE AR MODEL

Impulse response

The SASE intensity and the beam current shown in Figure 1 are analysed with the impulse response analysis

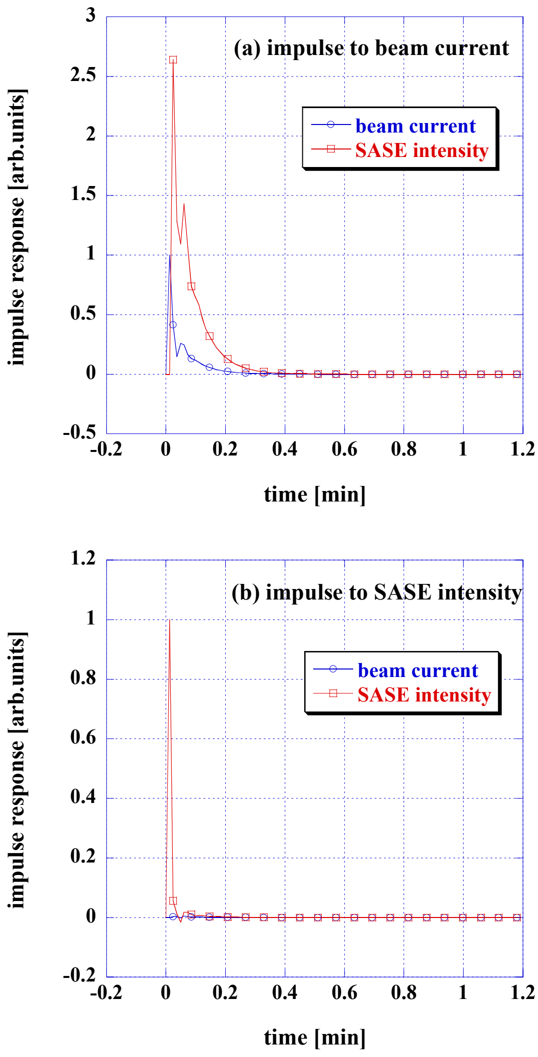

Figure 2: Impulse responses of the system for (a) impulse given to the beam current and (b) to the SASE intensity. The blue and the red lines indicate temporal responces of the beam current and the SASE intensity, respectively. The impulse given to the beam current influences the SASE intensity, but that to the SASE intensity does not affect the beam current.

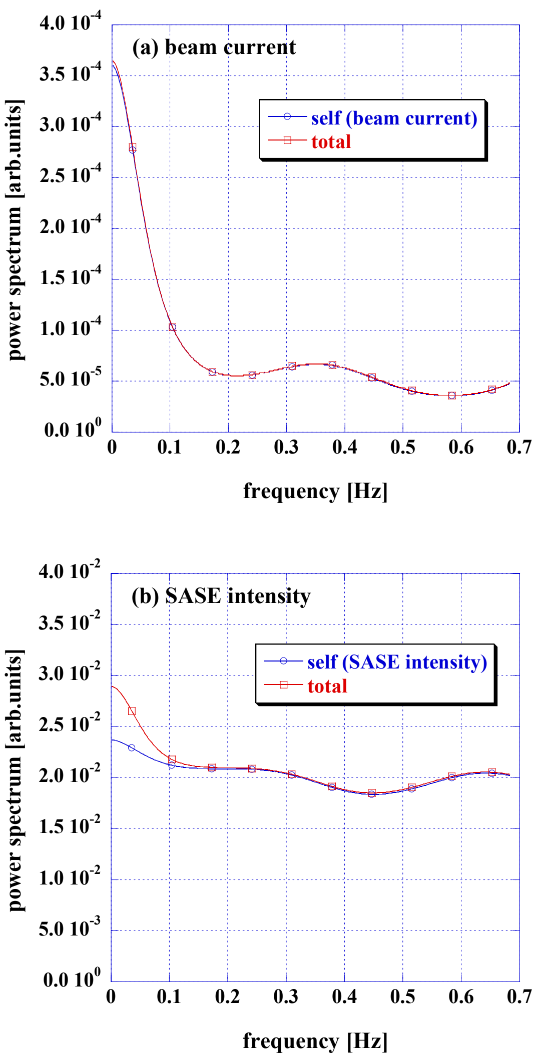

Figure 3: Power spectra (a) of the beam current and (b) of the SASE intensity. The red lines indicate the power spectra. The blue ones show spectra due to the own intrinsic noise power contributing to the power spectrum.

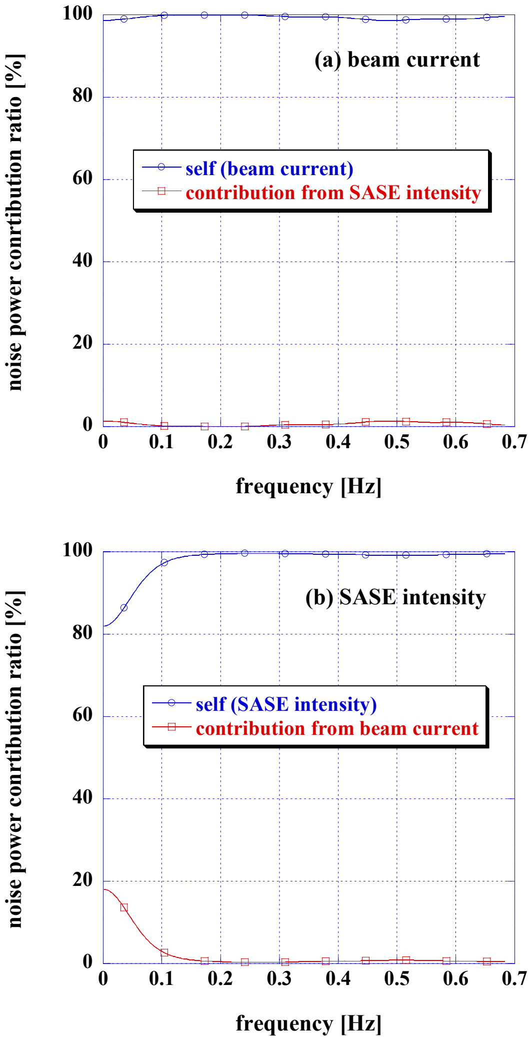

Figure 4: Noise contribution ratios (a) of the beam current and (b) of the SASE intensity. The blue and the red lines indicate the ratio of the power contribution due to the beam current to the power spectrum and that of the SASE intensity to the power spectrum, respectively.

method. Results of the analysis are shown in Figure 3, in which the order of the regressive number M is chosen to be 4 with the AIC for the measured data. The upper panel (a) shows the response of the system when the impulse is given to the beam current and the lower panel (b) to the SASE intensity. The vertical units in the figure are volts and the horizontal ones are minutes. When the beam jumps up from zero, SASE is generated and the intensity goes down gradually as the beam current decreases, but with a delay as shown in the panel (a). The result of the analysis is, (a): impulse to the beam current influences the SASE intensity, (b): impulse to the SASE intensity does not affect the beam current. The result is quite reasonable and does not contradict physical understanding. It shows that the AR model can be successfully applied to the measured data.

Power spectrum

Figure 3 shows results of the power spectrum analysis. The power spectrum of the beam current in the panel (a) shows that the frequency component less than 0.1 Hz is dominant and that the total spectrum is filled up with the power spectrum of the beam current, which indicates that the beam current is not influenced by the SASE intensity. On the other hand, the power spectrum of the SASE intensity in the panel (b) shows no significant peaks, and it is flat and constant over the frequency range shown in Figure 3. The total power spectrum in the panel (b), however, shows a peak centred at zero frequency, which indicates the contribution of the other component, or the beam current. This means that fluctuations of the measured SASE intensity is composed of the lower frequency component due to the beam current and the white component due to the intrinsic fluctuation of SASE.

Noise power contribution ratio

Figure 4 shows noise power contribution ratios of the power spectra shown in Figure 3. The beam current is not affected by the SASE intensity, but the SASE intensity is affected by the beam current in the frequency region lower than 0.1 Hz. The contribution ratio is about 18 % at the frequency of 0.01 Hz.

SUMMARY

In order to evaluate the contribution of the beam current to the intensity fluctuation of the SASE numerically, we measured the beam current and the SASE intensity simultaneously and analysed the measured data with the AR model. The results of the analysis show that the power spectrum due to the SASE intensity alone has no frequency dependence, while the peak shows up due to fluctuation of the beam current in the frequency region lower than 0.1 Hz, of the total power spectrum of the measured SASE intensity. The noise power contribution ratio of the beam current to the intensity fluctuation of SASE was evaluated to be 18 % in the period longer than 100 seconds.

REFERENCES

[1] R. Kato, et al., Nucl. Instr. and Meth. in Phys. Res. A 445 (2000) 164.
[2] R. Kato, et al., Nucl. Instr. and Meth. in Phys. Res. A 475 (2001) 334.
[3] R. Kato, et al., Nucl. Instr. and Meth. in Phys. Res. A 483 (2002) 46.
[4] H. Sakaki et al., T.SICE Vol.35, No.10 (1999) 1283-1291.
[5] R. Kato, et al., Nucl. Instr. and Meth. in Phys. Res. A 528 (2004) 244.
[6] H. Akaike, Ann. Inst. Statist. Math., Vol. 20 (1968) 425-439.
[7] H. Akaike, Ann. Inst. Statist. Math., Vol. 23 (1971) 163-180.
[8] H. Akaike, IEEE Trans. Vol. AC-19 (1974) 716-723.