STUDY OF ESASE SCHEME WITH MICROBUNCHING INSTABILITY FOR GENERATING ATTOSECOND-TERAWATT X-RAY PULSE IN XFELS*

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Abstract

Recent studies show that the attosecond terawatt X-ray pulse in XFELs can be generated by using ESASE (enhanced self-amplified spontaneous emission) scheme to obtain a sub-femtosecond spike in the electron peak current. However, ESASE scheme is not working properly when the microbunching instability is taken into account. The instability can be suppressed when the laser heater system, which increases the uncorrelated energy spread of the electron beam, is used in the injector. The effect of the microbunching instability on the performance of ESASE scheme will be discussed. In addition, the optimized results with the laser heater system for generating attosecond-terawatt X-ray pulse in XFELs is also presented.

INTRODUCTION

X-ray free-electron lasers have been successfully operated or will be operated to supply femtosecond X-ray pulses with a few tens of gigawatt power. However, an attosecond X-ray pulse is required to investigate the phenomena such as the dynamics of electrons in atoms, molecules and nanoscopic systems in their real time. The power of an attosecond X-ray pulse also have to be increased to the level of terawatts (TW) to deliver a sufficient number of photons.

There have been several proposals with quite low slice energy spread to generate attosecond X-ray pulse whose power is over 1 TW [1-6]. ESASE scheme [7] is applied to some methods to obtain high peak current spike in the electron beam as shown in Fig. 1. However, it is challenging to obtain the electron beam with quite low slice energy spread due to the laser heater system. Laser heater system increases the uncorrelated energy spread of the electron beam to suppress the microbunching instability [8].

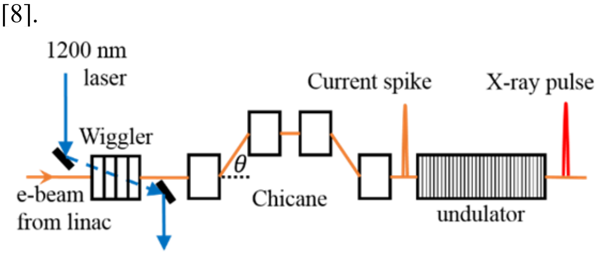

Figure 1: Layout of the ESASE scheme.

* Work supported by Max Planck POSTECH/KOREA Research Initiative Program [Grant No 2016K1A4A4A01922028] through the National Research Foundation of Korea (NRF) funded by Ministry of Science, ICT & Future Planning.
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In this research, ESASE scheme for generating attosecond TW X-ray pulse is investigated with different slice energy spread of the electron beam to reflect the effect of the laser heater system. FEL simulation results are also presented by using the results from the ESASE scheme.

MICROBUNCHING INSTABILITY

Microbunching instability, which is driven by coherent synchrotron radiation and longitudinal space charge, can be suppressed by laser heater system [8]. In the PAL-XFEL, such instability is also appeared from the ELEGANT [9] simulation result as shown in Fig. 2(a). Therefore, laser heater system has been installed and operated in the injector [10]. When the laser heater system is on, the microbunching instability is well suppressed as shown in Fig. 2(b) while the slice energy spread increases up to 1 MeV as listed in Table 1.

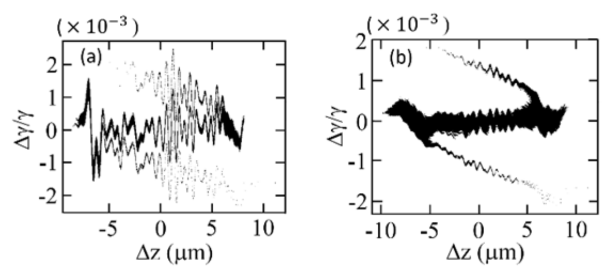

Figure 2: Bunch length – energy phase space at the PAL-XFEL linac end (a) without laser heater and (b) with laser heater.

Table 1: Main Parameters of Current PAL-XFEL

Parameter	Value	Unit
Energy	10	GeV
Undulator period	26	mm
Base current	3	kA
Normalized slice emittance	0.4	mm·mrad
Slice energy spread	1.0	MeV
Bunch length	20 (60)	μm (fs)
FEL wavelength	0.1	nm

ENHANCED-SASE SCHEME

When the slice energy spread is increased by laser heater system, properties of the current spike, which is obtained from ESASE scheme, is degraded as shown in Fig. 3: broadened width and lowered peak current. If the

ISBN 978-3-95450-182-3

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slice energy spread is doubled, the minimum width also doubled.

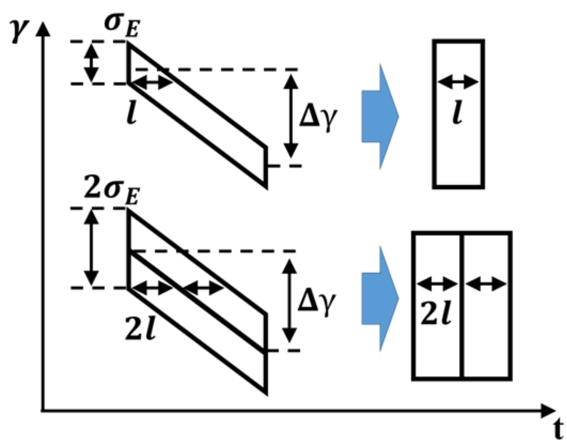

Figure 3: Schematic representation of the bunch compression in ESASE scheme for two cases which have the same energy difference (Δγ) and different slice energy spread (up: σ_E, down: $2\sigma_E$).

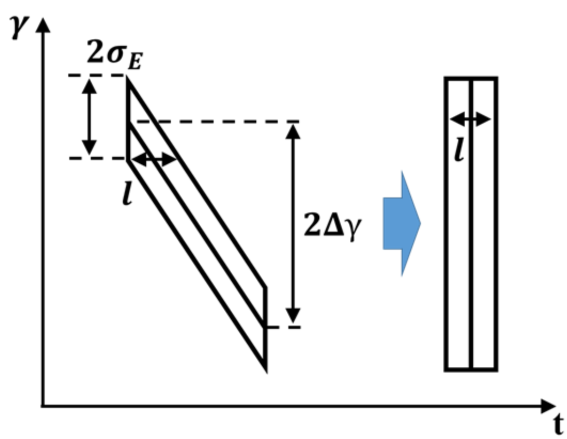

Figure 4: Schematic representation of the bunch compression in ESASE scheme for the case, which has 2Δγ energy difference and $2\sigma_E$ slice energy spread.

When the minimum width is doubled, the peak current is halved.

However, the degradation effect of the increased slice energy spread to the ESASE scheme can be overcome by increasing energy difference as shown in Fig. 4. When the slice energy spread is doubled, energy difference has to be also doubled. Then, the width of the current spike will be maintained and the peak current of the current spike can be preserved. From the ELEGANT simulation results as shown in Fig. 5, energy difference of the electron beam can be easily increased by using the input laser with higher energy.

The minimum width of the current spike with respect to the slice energy spread is shown in Fig. 6. The values of the slice energy spread which is used in the simulation are 0.25, 0.50. 0.75 and 1.00 MeV. To identify the validity of the schematic representation in Fig. 4 and Fig. 5, the simulations were conducted with various values of the energy difference (Δγ = 10, 20, 30 and 40). The normalized peak current of the current spike, which has the minimum width (Fig. 6), is shown in Fig. 7.

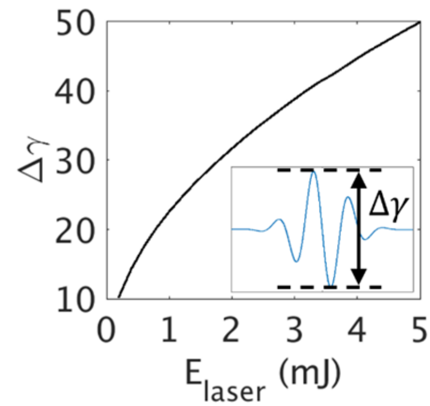

Figure 5: Δγ (see inset) after the wiggler with respect to the laser energy when the laser wavelength is 1200 nm. Inset: modulated electron beam energy along the bunch length after the wiggler.

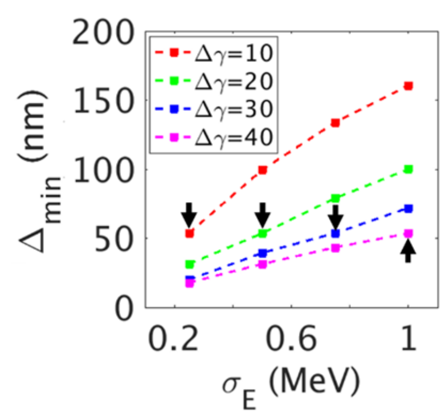

Figure 6: The minimum width of the current spike with respect to the slice energy spread.

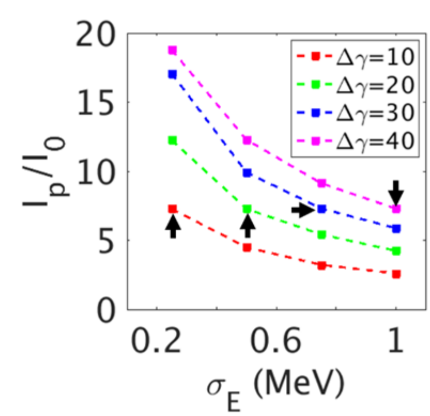

Figure 7: The normalized peak current of the current spike, which has the minimum width (Fig. 6) with respect to the slice energy spread.

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When the slice energy spread increases while the energy difference is maintained, the width of the current spike is increased and the peak current of that spike is decreased as predicted in Fig. 3. However, the cases, which is indicated by black arrows in Fig. 6 and Fig. 7, have nearly the same width and peak current of the current spike. These cases are similar with the case described in Fig. 4: the ratio between the slice energy spread and the energy difference is maintained by increasing the energy difference. Therefore, the increased slice energy spread from the laser heater system is no longer the problem to make narrow, high peak current spike.

FEL SIMULATION RESULTS

To investigate the effect of the slice energy spread on FEL performance, simulations are conducted with selected cases as indicated by black arrows in Fig. 6 and Fig. 7. These cases have nearly the same width and peak current of the current spike while the slice energy spread is different each other. GENESIS 1.3 [11] is used for FEL simulation and main parameters used in simulation are listed in Table. 1. The length of one planar undulator module is about 6 m and 10 modules (~60 m) are used in simulation. All results in this section use the averaged value from five results with random seeds to include shot noise effect.

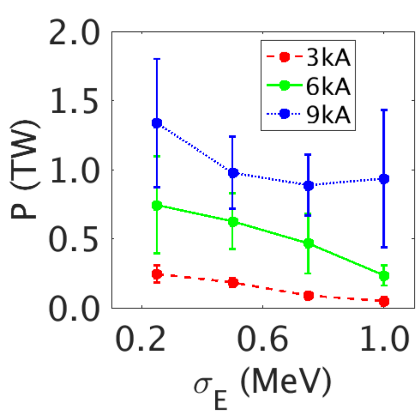

Figure 8: Maximum radiation peak power at the end of undulator line for different base current with respect to the slice energy spread of the electron beam.

Maximum radiation peak power at the end of undulator line is shown in Fig 8. The radiation peak power is decreased as the slice energy spread is increased. To compensate such FEL degradation, increasing the base current to gain higher peak current can be a possible solution.

When the base current is 9 kA, we can obtain about 1 TW, < 100 as X-ray pulse at 0.1 nm (12.4 keV) in spite of 1 MeV slice energy spread. However, it is challenging to suppress the background X-ray radiation from the quite high base current.

CONCLUSION

The slice energy spread at the end of linac is increased, when the laser heater system is applied to suppress the microbunching instability. When the laser power is increased to gain more energy difference as the slice energy spread increases, the same peak current and width of the current spike can be obtained from the ESASE section regardless of the slice energy spread. However, FEL degradation due to the raised slice energy spread cannot be avoided.

It can be a possible solution that the electron beam with high base current is used for generating attosecond terawatt X-ray pulse to compensate the increased slice energy spread by laser heater system. In this case, however, attosecond X-ray pulse may be degraded by strong background X-ray radiation generated from the high base current.

Therefore, careful investigation has to be carried out to find the optimal setting of the laser heater system for minimizing the slice energy spread increase, while the microbunching instability is sufficiently suppressed.

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