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GENERATION OF ISOLATED ZEPTOSECOND PULSE IN GAMMA-RAY FREE ELECTRON LASER*

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Abstract

An X-ray pulse with zeptosecond pulse duration is an essential tool to resolve the nuclear dynamics. To make such a short pulse duration, we need to make a very wide frequency range radiation which is known from the uncertainty principle. The spectral range of an isolated zeptosecond pulse has to be of order of few keV which is called as a gamma ray. In this presentation, the generation of an isolated zeptosecond pulses in the gamma-ray free electron laser is studied by the simulation.

INTRODUCTION

X-ray free-electron lasers have been successfully operated or will be operated to supply femtosecond X-ray pulses. To expand the research opportunities to investigate the ultrafast phenomena by using XFEL, lots of methods to generate an attosecond X-ray pulse from XFEL has been also proposed. However, time-resolved investigation of nuclear processes such as resonance internal conversion, compound nuclei evolution or photodisintegration of nuclei needs shorter radiation pulse duration which is about few or sub attosecond [1]: Territory of zeptosecond science.

According to the uncertainty principle, the frequency spectrum of isolated zeptosecond pulse has to be sufficiently wide which is about few keV order. So, the resonance wavelength of undulator has to be moved to the gamma-ray range in the XFELs. We did choose the 0.01 nm wavelength to make a zeptosecond pulse. The appropriate rms undulator parameter (a_w) according to the undulator period and electron beam energy is shown in Fig. 1.

Black dashed line in Fig. 1 indicates the technical limit which means that the undulator gap is 0 from Halbach formula. For the simulation in this research, we select the energy of electron beam as 17.5 GeV which is same as European XFEL case and the undulator period as 13 mm. This choice can open the chance of the upgrade of Euro-XFEL in the future.

CURRENT SPIKES GENERATION

To generate isolated ultrafast radiation pulse, short current spikes are required and it can be generated by using enhanced-self amplified spontaneous emission (E-SASE) scheme [2] as shown in Fig. 2. When the electron beam passes through a wiggler with modulation laser pulse, energy modulation of the electron beam is induced by resonance condition of the wiggler. Such energy modulation is converted to the current modulation in the follow up chicane by virtue of R_{56}. When the modulation laser consists of series of few-cycle pulses by using chirped laser or laser pulse stacking method, irregularly spaced current spikes is generated from the E-SASE section [3].

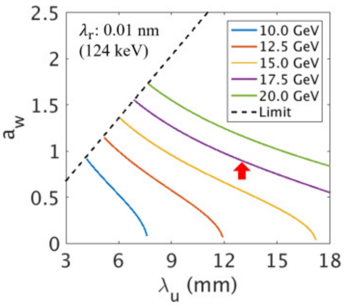

Figure 1: rms undulator parameter vs. undulator period according to electron beam energy when the resonance wavelength is 0.01 nm (124 keV). Red arrow indicates simulation point.

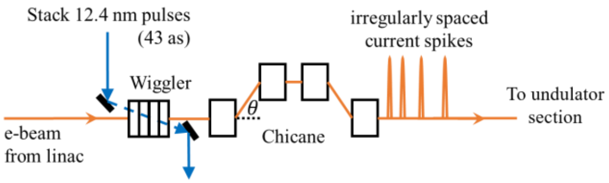

Figure 2: E-SASE scheme to generate current spikes.

To generate sufficiently short current spikes, a soft X-ray attosecond pulse of which duration is 43 as [4] is used to modulate the energy of electron beam. Phase space of the electron beam after wiggler is shown in Fig. 3(a). Energy difference between maximum point and minimum point is about 10 MeV. Phase space of electron beam after chicane is shown in Fig. 3(b).

Table 1: Main Parameters Used in Simulation

Parameter	**Value**	**Unit**
Energy	17.5	GeV
Undulator period	13	mm
Base current	5	kA
Normalized slice emittance	5	nm·rad
Slice energy spread	0.5	MeV
Bunch length	3 (10)	μm (fs)
FEL wavelength	0.01	nm

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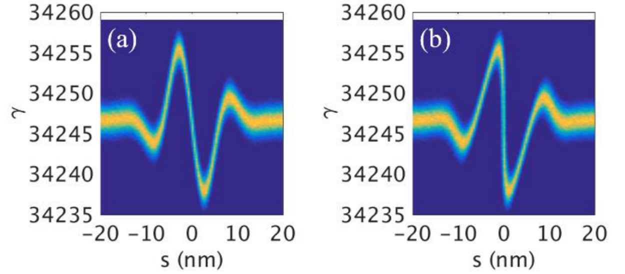

Figure 3: Phase space (energy vs. longitudinal position) of the electron beam (a) after wiggler and (b) after chicane of E-SASE section.

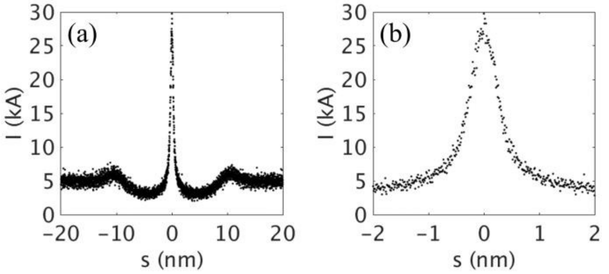

Figure 4: (a) Current along the electron beam after chicane of E-SASE section. (b) Main current spike in (a) of which FWHM is about 1 nm.

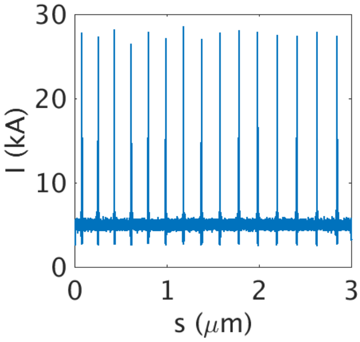

Figure 5: 15 current spikes used in simulation.

When the proper R_{56} is applied to electron beam by chicane, high current spike can be obtained as shown in Fig. 4(a). In our case, peak current of current spike is about 30 kA and duration of current spike is about 1 nm as shown in Fig. 4(b).

When 15 attosecond pulses are irregularly stacked and used to modulate the energy of electron beam, 15 irregularly spaced current spikes is generated as shown in Fig. 5. This current profile is used in simulation to generate isolated zeptosecond radiation pulse.

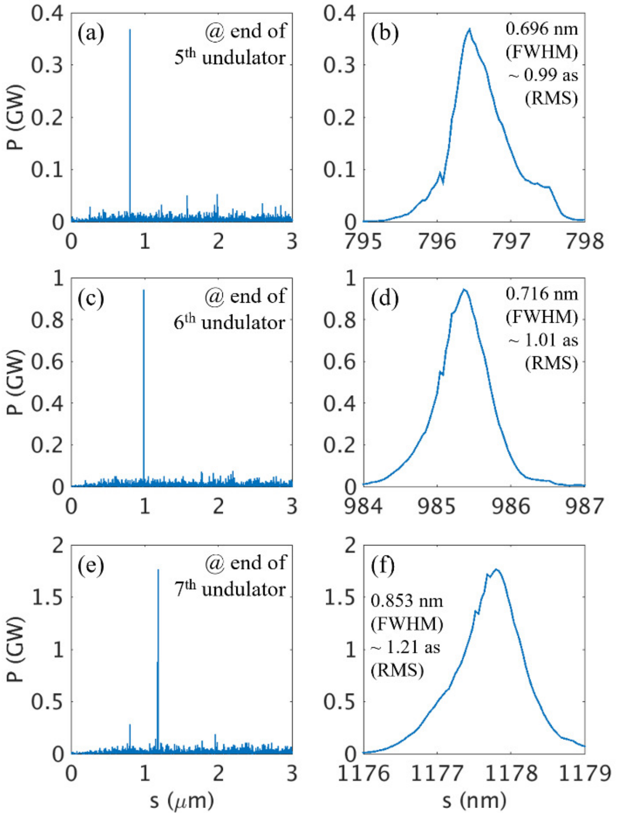

Figure 7: Radiation power along the electron beam at the end of (a, b) 5th undulator, (c, d) 6th undulator and (e, f) 7th undulator. (b, d, f) Main radiation pulse shape in (a, c, e).

ISOLATED PULSE GENERATION

Schematic layout of undulator line for the scheme which can generate isolated pulse by using irregularly spaced current spikes is shown in Fig. 6. When the electron beam delay between undulators is optimized, only selected radiation pulse proceeds the amplification process and isolated pulse is generated in spite of multi current spikes.

After 5th undulator, a zeptosecond pulse with 0.99 as (RMS) is obtained even though the peak radiation power is only 0.38 GW as shown in Fig. 7(a) and (b). To in-crease the radiation power, we can proceed the amplifica-tion procedure by using 6th undulator. The radiation pow-er is increased up to 0.94 GW as shown in Fig. 7(c) and (d). However, the pulse duration is also increased to 1.01 as. If we use 7th undulator also, we can increase the radiation power to over 1.8 GW with 1.21 as which is shown in Fig. 7 (e) and (f).

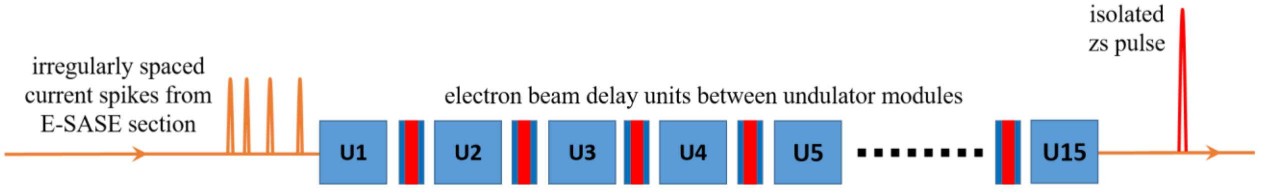

Figure 6: Schematic layout of undulator line for generating isolated pulse. Electron beam delay unit is installed in the energy intersection between undulator modules.

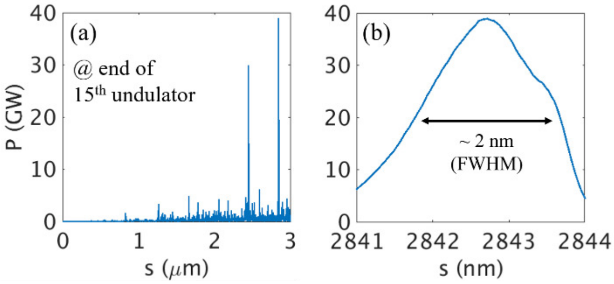

Figure 8: (a) Radiation power along the electron beam at the end of undulator line (end of 15th undulator). (b) Main radiation pulse in (a) of which FWHM is about 2 nm (2.83 as).

To get a clean signal from the scattering experiment, we need enough number of photons at the detector. If we use 15 undulators in the amplification procedure, we can get almost 40 GW radiation power at the main radiation peak as shown in Fig. 8. However, the pulse duration also increased over 2.83 as. One more problem is the side peaks which is behind the main peak.

SUMMARY

By using 15 attosecond soft X-ray pulses, we did make 15 current spikes which length is about 1 nm in FWHM. We 15 undulator sections in which there are chicane type delay units to delay the current spikes to amplify only one radiation spike. We can get almost 40 GW radiation power with 2.83 as (RMS) pulse duration.

We need to increase the radiation power more than 1 TW with keeping the radiation duration 1 as (RMS). We will do more simulation to find the condition in which such a wonderful zeptosecond radiation pulse is generated from the XFELs in the future.

REFERENCES

[1] M. Klaiber, K. Z. Hatsagortsyan, and C. H. Keitel, “Zeptosecond γ-ray pulses,” http://arXiv.org/abs/0707.2900 (2007).

[2] A. A. Zholents, “Method of an enhanced self-amplified spontaneous emission for x-ray free electron lasers”, Phys. Rev. ST Accel. Beams **8**, 040701 (2005).

[3] T. Tanaka, Y. W. Parc, Y. Kida, R. Kinjo, C. H. Shim, I. S. Ko, B. Kim, D. E. Kim, and E. Prat, “Using irregularly spaced current peaks to generate an isolated attosecond X-ray pulse in free-electron lasers”, J. Synchrotron Rad. **23**, 1273 (2016).

[4] T. Gaumnitz, A. Jain, Y. Pertot, M. Huppert, I. Jordan, F. Ardana-Lamas, and H. J. Wörner, “Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver,” Opt. Express **25**, 27508 (2017).