ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P15

MULTICHROMATIC FREE-ELECTRON LASER GENERATION THROUGH FREQUENCY-BEATING IN A CHIRPED ELECTRON BEAM

Zheng Qi[1,*], Chao Feng[1,2]
[1]Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China
[2]University of Chinese Academy of Sciences, Beijing, China

Abstract

We propose a simple method to generate mode-locked multichromatic free-electron laser (FEL) through a longitudinal phase space frequency-beating in a chirped electron beam. Utilizing the two stage modulator-chicane setups in Shanghai Soft X-ray FEL facility, together with a chirped electron beam, we are going to imprint a frequency-beating effect into the electron beam. Hence periodic bunching trains can be formed and can be used to generate mode-locked FEL radiation pulses. Theoretical analysis and numerical simulations are given out to demonstrate the performance of the method. The results indicate that mode-locked FEL in temporal and frequency domain can be formed at the 18th harmonic of the seed laser, with the central wavelength being about 14.58 nm and the peak power over 2 GW.

INTRODUCTION

Mode locking is an essential concept and technique in conventional lasers. It's of great importance in the generation of ultrashort laser pulses and in the stable control of the laser phase.For the state-of-the-art X-ray free electron lasers, mode-locked lasing has also been proposed and pursued for the last decade [1, 2]. Mode-locked XFELs could provide new opportunities for high resolution x-ray spectroscopy and attosecond sciences. The FEL community has proposed and studied several methods for mode-locked FEL lasing. Generally mode-locked FEL lasing requires an initial energy modulation or density modulation with fixed phase relation imprinted into the electron beam. And then mode locking amplifiers with undulator and delay-chicane modules are needed for the amplification.

In this study, we propose a simple method to generate mode-locked multichromatic FEL through a longitudinal phase space frequency-beating in a chirped electron beam. The schematic layout is show in Fig 1. The layout mainly consists of two modulator-chicane setups and a radiator. The electron beam is coming from the upstream beam switchyard, and it is manipulated to have an energy chirp in the head and tail of the electron beam. Two seed lasers with identical wavelength are employed in the two modulator. The chirped electron beam first get an energy modulation in modulator-1, the chicane-1 with a relatively small dispersion will then slightly change the imprinted energy modulation wavelength since the whole electron beam has an energy chirp. The electron beam will then get an energy modulation in modulator-2, and in chicane-2 the energy modulation is converted into density modulation. Through proper optimizations of the parameters, periodic bunching trains can be formed in the electron beam, and high harmonic bunching can also be formed. And then the electron beam will go through the radiator for mode-locked high-gain harmonic generation (HGHG) FEL radiation.

We will give a brief analysis of the electron beam phase space evolution in the scheme. First of all, we need to define some variables. The dimensionless energy deviation of a particle is defined as $p = (E - E_0)/\sigma_E$, where E_0 is the central energy of the electron beam and σ_E is the rms energy spread. The initial longitudinal beam distribution can be written as

$$f(p) = \frac{1}{\sqrt{2\pi}} exp(-p^2/2) \tag{1}$$

with a linear energy chirp and an energy modulation, the electron beam energy becomes

$$p_1 = p + c\frac{E_0}{\sigma_E \sigma_s} z + A_1 \sin(k_1 z) \tag{2}$$

where c is the relative linear energy chirp,A_1 is the energy modulation strength, k_1 is the wavenumber of the seed laser. After DS1, the electron longitudinal position becomes

$$z_1 = z + R^1_{56} p_1 \sigma_E / E_0 \tag{3}$$

and the beam distribution now is

$$\begin{aligned} f(p,z) &= \frac{1}{\sqrt{2\pi}} exp\{-\frac{1}{2}[p - c\frac{E_0}{\sigma_E\sigma_s}(z - R^1_{56} p \sigma_E/E_0) \\ &\quad - A_1 \sin(k_1(z - R^1_{56} p\sigma_E/E_0))]^2\} \\ &= \frac{1}{\sqrt{2\pi}} exp\{-\frac{1}{2}[p - \frac{cE_0}{\sigma_E\sigma_s} z + cR^1_{56} p/\sigma_s \\ &\quad - A_1 \sin(k_1 z - R^1_{56} k_1 p \sigma_E/E_0)]^2\} \end{aligned} \tag{4}$$

define $C = \frac{cE_0}{\sigma_E\sigma_s}$,$\xi = k_1 z$,$B_1 = R^1_{56} k_1 \sigma_E/E_0$, we can simplify the formula as follows

$$\begin{aligned} f(p,\xi) &= \frac{1}{\sqrt{2\pi}} exp\{-\frac{1}{2}[p - C\xi/k_1 + CB_1 p/k_1 \\ &\quad - A_1 \sin(\xi - B_1 p)]^2\} \end{aligned} \tag{5}$$

through the second energy modulation and the second dispersion section, the electron beam energy and the electron longitudinal positions are now

$$\begin{aligned} p_2 &= p_1 + A_2 \sin\xi \\ z_2 &= z_1 + R^2_{56} p_2 \sigma_E/E_0 \end{aligned} \tag{6}$$

* qiz@sari.ac.cn

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P15

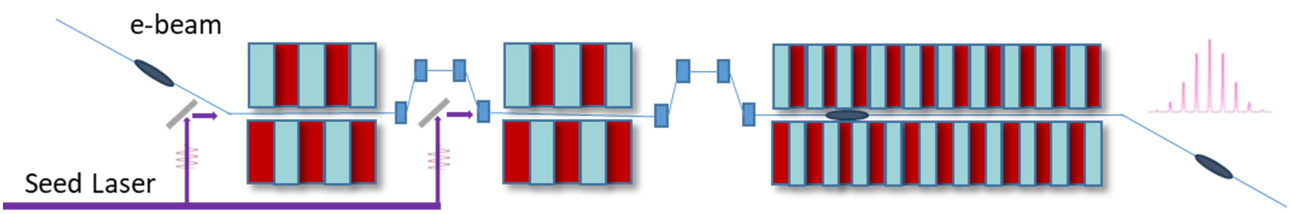

Figure 1: Schematic layout of the method

and the beam distribution is now

$$f(p,\xi) = \frac{1}{\sqrt{2\pi}} exp\{-\frac{1}{2}\{p - A_2 \sin(\xi - B_2 p) \\ - C/k_1[\xi - (B_1 + B_2)p + A_2 B_1 \sin(\xi - B_2 p)] \\ - A_1 \sin[\xi - (B_1 + B_2)p + A_2 B_1 \sin(\xi - B_2 p)]\}^2\} \tag{7}$$

in which $B_2 = R_{56}^2 k_1 \sigma_E / E_0$. Integration of this formula over p gives the beam density N as a function of ξ, $N(\xi) = \int_{-\infty}^{\infty} dp f(\xi, p)$, and the bunching factor of the nth harmonic can be written as

$$b_n = \left|\langle e^{-in\xi} N(\xi)\rangle\right| \tag{8}$$

SIMULATION

Using the main paramters in Tab. 1, we demonstrate the 3-dimentional electron beam and FEL simulation results. Firstly we can see the longitudinal phase space distribution in Fig 2 from Eq 7. One can find out that the frequency-beating effect is formed in the electron beam. And there exits three beating peaks and valleys respectively. We derived the high harmonic bunching of this longitudinal phase space distribution. The 18th harmonic bunching factor at the entrance of the undulator is shown in Fig 3. We can see three bunching peaks in the electron beam. And the maximum bunching factor is about 0.12, which is sufficient enough for the HGHG FEL radiation.

Table 1: Main Parameters

Parameter	Value	Unit
Electron beam energy	1000	MeV
Beam energy chirp	0.5	%
Slice energy spread	40	keV
Peak current	1500	A
Emittance	1.0	mm·mrad
Seed laser wavelength	264	nm
Modulation-1 amplitude	4	-
Chicane-1 dispersion	160	μm
Modulation-2 amplitude	5.5	-
Chicane-2 dispersion	30	μm

We conducted FEL simulation using Genesis 1.3. FEL radiation power and spectra results are shown respectively in Fig 4 and Fig 5. We can see the FEL radiation has three

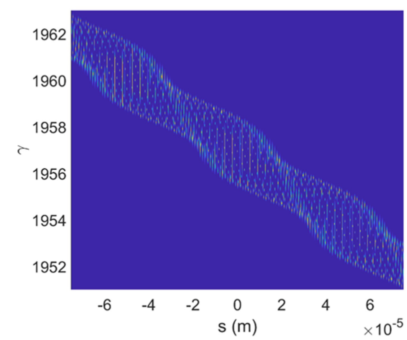

Figure 2: Electron beam longitudinal phase space distribution at the entrance of the radiator.

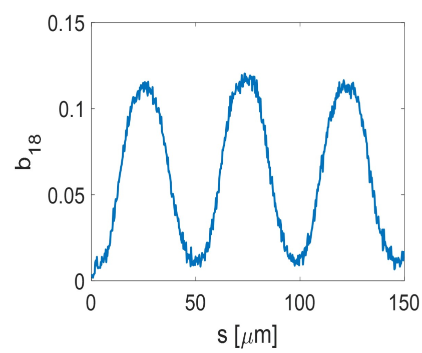

Figure 3: The 18th harmonic bunching factor at the entrance of the radiator.

correspondent peaks in the temporal domain. And the peak power can reach above 2 GW. Due to the energy chirp of the electron beam, the radiation processes of the three peaks are slight different. So the power profiles of the three peaks are not the same. We can also see the mode-locked properties of the FEL in Fig 5. The central wavelength is about 14.58 nm, which is a little bit shorter than the 18th harmonic of the seed laser. That is due to the decreased K-tuning of the undulator field for the amplification of all the three bunching peaks. The mode-locked FEL spectra also show several sideband, that is mainly due to the slippage effect.

CONCLUSION

We studied a simple method to generate mode-locked multichromatic FEL radiation pulses. Using the two modulator-chicane setups in SXFEL and a chirped electron beam, we

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-WE4P15

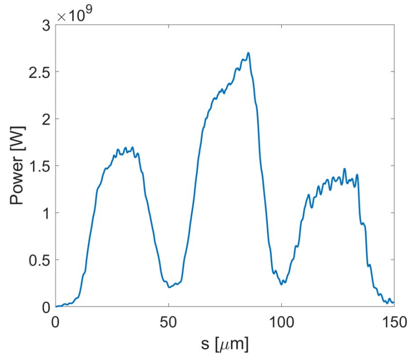

Figure 4: FEL radiation power.

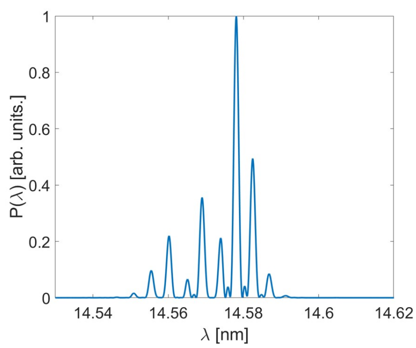

Figure 5: FEL radiation spectra.

can imprint periodic bunching trains into the electron beam. And then we can get mode-locked multichromatic FEL radiation. The simulation results demonstrate that high harmonic bunching up to 18th harmonic of the seed laser can be achieved, and mode-locked FEL lasing with a peak power of above 2 GW can be generated. We want to mention that the method we proposed here can be easily implemented in FEL facilities with two modulator-chicane setups. And the method is also quite suitable for high energy Terahertz FEL radiation since the frequency-beating structure is at the same scale of the Terahertz wavelength.

ACKNOWLEDGEMENTS

We thank Kaiqing Zhang for helpful discussions. Work is supported by National Natural Science Foundation of China 12275340.

REFERENCES

[1] N. R. Thompson, and B. W. J. McNeil, "Mode locking in a free-electron laser amplifier", *Phys. Rev. Lett.*, vol. 100, no. 20, p. 203901, 2008. doi:10.1103/PhysRevLett.100.203901

[2] P. K. Maroju *et al.*, "Attosecond pulse shaping using a seeded free-electron laser", *Nature* vol. 578, no. 7795, pp. 386-391, 2020. doi:10.1038/s41586-020-2005-6