GENERATION OF COHERENT MODE-LOCKED RADIATION IN A SEEDED FREE ELECTRON LASER

Zhen Wang[1,2], Dao Xiang[3,4], Zhentang Zhao[1,2*]
[1]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2]Shanghai Sciences Research Center, Chinese Academy of Sciences, Shanghai 201204, China
[3]Key Laboratory for Laser Plasmas (Ministry of Education), Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[4]Collaborative Innovation Center of IFSA (CICIFSA), Shanghai Jiao Tong University, Shanghai 200240, China

Abstract

We present the promise of generating mode-locked multichromatic radiations in a seeded free electron laser based on high gain harmonic generation (HGHG). 3D start-to-end simulations have been carried out and analysis & comparisons have been made to have a research on the properties of each system. In these schemes, either the seed laser intensity or the electron beam density is modulated to produce a coherent radiation pulse train that yields multiple spectral lines in FEL output. Stable peak power at gigawatt level can be generated in the undulator finally.

INTRODUCTION

Free electron lasers (FELs) [1] capable of generating coherent x-ray radiation with high brightness and ultra-fast time structures, will enable scientists in physics, chemistry, biology and medicine to study nature down to the molecular and atomic level [2]. For nowadays, most shot-wavelength FEL facilities, such as FLASH [3] in Germany, LCLS [4] in US, SACLA [5, 6] in Japan and under-constructing Swiss-FEL in Switzerland, European-FEL in Germany, Pal-FEL in Korea, LCLS-II in US, make use of the self-amplified spontaneous emission (SASE) scheme [7, 8]. However, the SASE scheme can provide stable output pulse energy and good spatial coherence but limited temporal coherence due to its starting from the shot noise. Later on, the "self-seeding" scheme [9-11], the enhanced-SASE (eSASE) scheme [12] and improved-SASE (iSASE) scheme [13] are proposed and demonstrated, in order to improve the SASE-FEL performance and provide full-temporal coherent, ultra-short pulse length and ultra-intense radiation. In the past decade, FEL has been witnessed an impressive development and now the growing user demands lead to the continuing enhancement of the facility capabilities, such as the mode-locked FEL schemes [14-17] and the two-colour FEL schemes [18-20].

As suggested in Ref. [15], a short undulator is added upstream of the self-seeding beam line to produce a density-modulated electron beam, converting a single-frequency coherent seed into a multi-colour output radiation at X-ray wavelength. Here we propose and compare two representative schemes for the generation of a similar output at the extreme UV wavelength, which may find its application on for-wave-mixing experiments [21, 22], the generation of isolated attosecond pulse (IAP) driven by multi-colour gating [23] and pump-probe experiments [24, 25].

In the first scheme, a longitudinal-shaped seed laser, generated by a pulse stacker [26] or BBO crystals, is used to modulate the electron beam to produce a coherent radiation pulse train. In the second scheme, an emittance spoiler foil [27, 28] with a series of vertical slots is inserted in the center of the bunch compressor chicane, aiming to generate an electron bunch train. The front method is based on modulating the envelop intensity of the seed laser while the back one based on modulating the electron beam density. In both schemes, the slippage length is shorter than the separation of the pulse trains, such that the radiation pulse copies the initial bunching profile that lead to a multi-colour output.

In this paper, we present the comparative study on these schemes using the beam parameters of the Dalian Coherent Light Source (DCLS), which will be China's first FEL user facility based on the HGHG scheme, as shown in Fig.1. The linac of DCLS consists of an S-band injector, an X-band RF structure as the longitudinal phase space linearizer, an S-band main accelerator (L1 and L2) and a bunch compressor chicane (BC), which can provide several-picosecond electron beam with the energy up to 300MeV and the charge of 500 pC. As designed for HGHG operation, the undulator system consists of a modulator (Mod), dispersion section (DS) and a radiator (Rad). The seed laser system is a Ti:Sapphire laser with the OPA system, aiming to provide tunable-wavelength laser with the wavelength from 200 nm to 350 nm. The main parameters are listed in table 1.

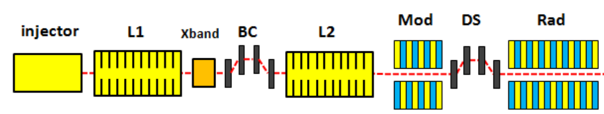

Figure 1: Layout of the DCLS facility.

In order to illustrate the performance of multi-colour FEL radiation on DCLS, start-to-end simulations had been carried out based on three-dimensional tracking code ASTRA [29] (for the simulation in the injector), ELEGANT [30] (for the simulation for the remainder of the linac) and GENESSIS [31] (for the simulation of FEL performance).

*Email: zhaozhentang@sinap.ac.cn

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Table 1: Main Linac Parameters of DCLS

Beam energy (MeV)	300	MeV
Peak current	400	A
Charge	500	pC
Bunch length (FWHM)	2	ps
Transverse emittance	1	mm*mrad
Wavelength of seed laser	200-350	nm
Period length of modulator	50	mm
Period length of radiator	30	mm
Wavelength of radiation	50-150	nm

METHOD I: MULTI-COLOUR RADIATION BASED ON SEED LASER TRAIN

As we mentioned above, DCLS could provide several-picosecond electron beam with the energy up to 300 MeV and the charge of 500 pC. In our operation, an 8 ps electron beam is generated in the photocathode gun with the charge of 500 pC and the peak current of 50 A. The electron beam is then boosted to 130 MeV in L1 and compressed to about 400 A in BC. Finally, L2 is used to future accelerate the electron beam to 270 MeV with the pulse length of 2 ps at the end of the linac. The longitudinal phase space of the electron beam is shown in Fig. 2.

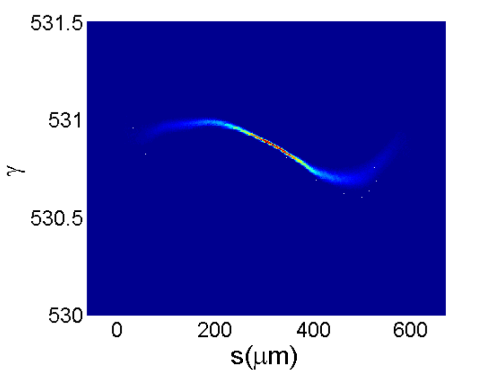

Figure 2: Longitudinal phase space of the electron beam at the end of the linac.

To generate seed laser train, the pulse stacker or BBO crystal technique is employed. In our scheme, a seed laser pulse train is generated with the pulse length of 30 fs, the interpulse spacing of 200 fs and the peak power of 10MW and is used to modulate the electron beam, aiming to generate 61 keV energy modulation in the modulator with 20 periods and a period length of 50 mm. The central wavelength of the seed laser train is 264 nm with 4 pulses in it. The electron beam is well energy-modulated in the modulator where the power of the seed is high enough and the energy modulation is converted into density modulation after the dispersion section (DS) with the bunching factor of the 4th harmonic is about 0.18 at the entrance of the radiator. The results of the FEL simulation performance are shown in Fig. 3, from which we can see it clearly that the multi-colour FEL radiation at the central wavelength of 66 nm is produced and the peak power of the radiation quickly increases to 0.12 GW after the electron beam passing through a 6 m long radiator. The relative FWHM bandwidth of the radiation is about 0.2%. The central wavelength of the mode-locked radiation, which has a fixed phase relationship (coming from the seed laser) between these radiation modes due to some coupling mechanism, could be tuned continuously by varying the wavelength of the seed laser and the gap of the undulator. The separation of the spectral lines could be tuned as well by varying the interpulse spacing of the seed laser.

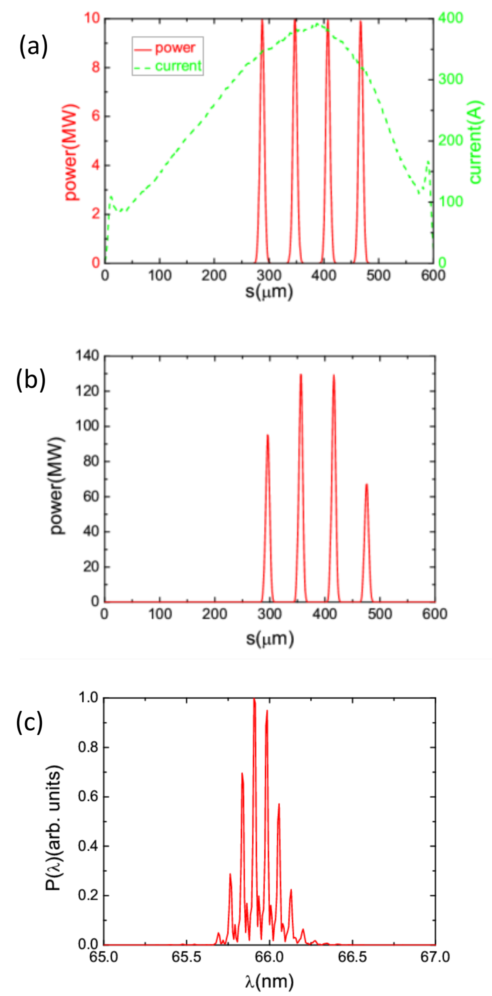

Figure 3: Simulations for FEL performance: (a) relative position of the seed laser pulse and the electron current; (b) output radiation pulse; (c) radiation spectrum.

METHOD II: MULTI-COLOUR RADIATION BASED ON EMITTANCE SPOILER TECHNIQUE

The emittance spoiler technique is initially proposed for the generation of ultra-short X-ray radiation pulses [22]. By adding an emittance spoiler foil with vertically oriented narrow slots in the central of the bunch compressor chicane, the emittance of most of the electron

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beam will be spoiled while leaving only short unspoiled parts to produce radiation pulses much shorter than the total electron bunch. It is proved to be quite a suitable way to generate the electron pulse train with a series of slots on the foil.

In this scheme, the electron beam with the charge of 500pC and the peak current of 400A is used, which is the same with that in method I. Then a 4-slot foil (3 μm Aluminum foil with the slot width of 0.2 mm and the separation of 0.8 mm) is inserted in the middle of the bunch compressor chicane, aiming to generate a 4-pulse electron train with the pulse length of about 50fs and the separation of 170 fs. The R_{56} of the chicane is 47.1 mm and the horizontal dispersion of the chicane is about 0.25 m. The longitudinal phase space of the electron pulse trains at the exit of the linac is shown in Fig. 4. One can vary the electron pulse train parameters by changing the slot width and the separation on the foil.

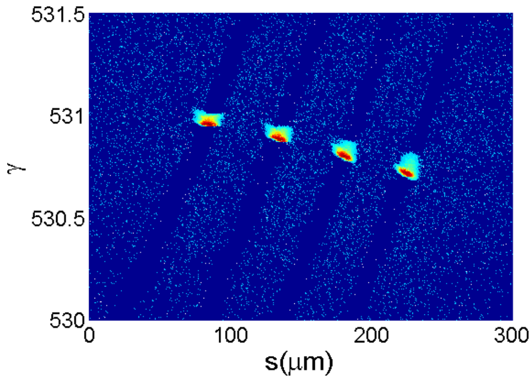

Figure 4: Longitudinal phase space of the electron pulse train. The spoiled part of the electron beam makes little contribution to the radiation.

After being generated in the linac, the relativistic electron pulse train is modulated by an 8-ps seed laser at the wavelength of 264 nm and the peak power of 10 MW, generating 65 keV energy modulation in the beam phase space in the modulator. The electron pulse train is well bunched after the dispersion section (DS), and the bunching factor of the 4th harmonic is about 0.17 at the entrance of the radiator. The simulation results of FEL performance are illustrated in Fig. 5, from which we can see it clearly that the peak current of the electron pulse train is much higher (600 A) than that without the slotted foil inserted in the chicane because part of the electrons hitting the foil are scattered to overlap with the unspoiled electrons. The emittance of those scattering electrons increases to more than 10 mm mrad, which makes little contribution to the FEL radiation. The peak power of the radiation increase quickly to 0.12 GW along 6 m radiator and the relative FWHM bandwidth of the radiation is about 0.2%. One can vary the interline spacing and the bandwidth of the mode-locked radiation by varying the slot width and separation on the foil.

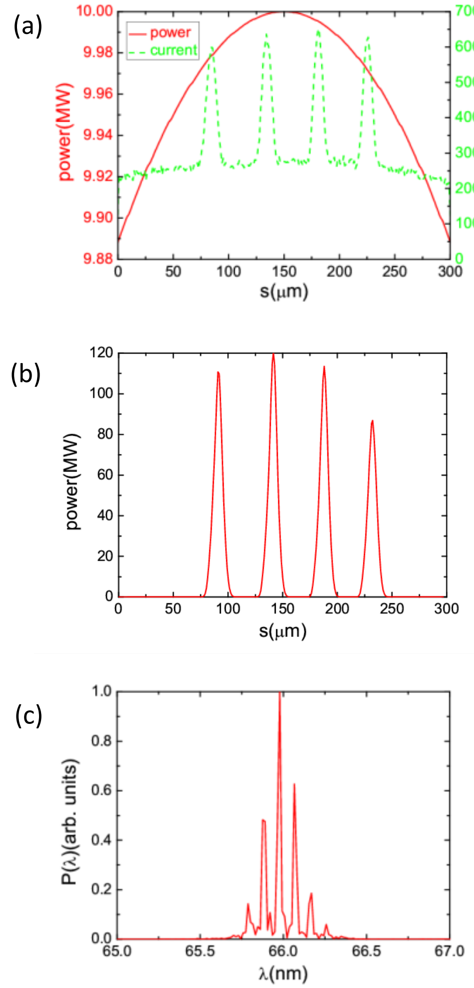

Figure 5: Simulations for FEL performance: (a) relative position of the seed laser pulse and the electron current; (b) output radiation pulse; (c) radiation spectrum.

CONCLUSIONS

In this paper, we have presented the study on two representative methods to produce coherent multi-colour UV FEL radiation based on HGHG scheme. The simulation results show that both methods are quite efficient to generate mode-locked radiation with gigawatt level peak power. At the same time, it is also quite convenient to vary the bandwidth and the interline space of the radiation spectrum, which allows us to design the pulse distribution, thus the experiment according to the user's demands.

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REFERENCES

[1] J. M. J. Madey, J. Appl. Phys. 42, 1906 (1971).
[2] B. W. J. McNeil and N. R. Thompson, Nat. Photonics 4, 814 (2010).
[3] W. Ackermann, G. Asova, V. Ayvazyan *et al.*, Nat. Photonics1, pp. 336-342 (2007).
[4] P. Emma, R. Akre, J. Arthur*et al.*, Nature Photonics 4, pp. 641-647(2010).
[5] D. Pile, Nature Photonics 5, pp. 456-457 (2011).
[6] Z. Huang and L. Lindau, Nature Photonics 6, pp. 505-506 (2012).
[7] A. Kondratenko and E. Saldin, Part. Accel. 10, 207 (1980).
[8] R. Bonifacio, C. Pellegrini and L. M. Narducci, Opt. Commun. 50, 373 (1984).
[9] J. Amann, W. Berg, V. Blank *et al.*, Nature Photonics 6, pp. 693-698 (2012).
[10] T. Inagaki, N. Adumi, T. Fukui *et al.*, proceedings of IPAC2014, Dresden, Germany, paper THPRO016.
[11] A. A. Lutman, F.-J Decker, J. Arthur *et al.*, Phys. Rev. Lett. 113, 254801 (2014).
[12] A. A. Zholents, Phys. Rev. ST Accel. Beams 8, 040701 (2005).
[13] J. Wu, A. Marimelli, C. Pellegrini, in Proceedings of FEL 2012, Nara, Japan, paper TUPD07.
[14] N. R. Thompson and B. W. J. McNeil, Phys. Rev. Lett. 100, 203901 (2008).
[15] D. Xiang, Y. Ding, T. Raubenheimer *et al.*, Phys. Rev. ST Accel. Beams 15, 050707 (2012)
[16] C. Feng, J. Chen, Z. Zhao Phys. Rev. ST Accel. Beams 15, 080703 (2012).
[17] D. J. Dunning, B. W. J. McNeil and N. R. Thompson, Phys. Rev. Lett. 110, 104801 (2013).
[18] A. A. Lutman, R. Coffee, Y. Ding *et al.*, Phys. Rev. Lett. 110, 134801 (2013).
[19] A. A. Lutman, F.-J Decker, J. Arthur *et al.*, Phys. Rev. Lett. 113, 254801 (2014).
[20] A. Marinelli, D. Ratner, A. A. Lutman *et al.*, Nature Commun. 6, 6369 (2015).
[21] F. Bencivenga, S. Baroni, C. Carbone *et al.*, New Journal of Physics 15, 123023 (2013).
[22] A. Perrin, C. M. Savage, D. Boiron *et al.*, New Journal of Physics 10, 045021 (2008).
[23] Q. Zhang, L. He, P. Lan *et al.*, Optics Express 22, 13213 (2014).
[24] F. Bencivenga, F. Capotondi, F. Casolari et al., Faraday Discuss. 171, 487 (2014).
[25] K. Schnorr, A. Senftleben, G. Schmid et al., Faraday Discuss. 171, 41 (2014).
[26] C. W. Siders, J. L. W. Sider, A. J. Taylor *et al.*, Applied Optics, Vol. 37, No. 22, 1 August (1988).
[27] P. Emma, K. Bane, M. Cornacchia*et al.*, Phys. Rev. Lett. 92, 074801 (2004).
[28] P. Muggli, V. Yakimenko, M. Babzien *et al.*, Phys. Rev. Lett. 101,054801 (2008).
[29] ASTRA tracking code, http://tesla.desy.de/~meykopff/
[30] M. Borland, Advanced Photon Source LS-287, September 2000.
[31] S. Reiche, Nucl. Instrum. Methods A, pp. 429-243 (1999).