TWO-COLOR FEL SCHEMES BASED ON EMITTANCE-SPOILER TECHNIQUE

C. Feng, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA,
Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China
Y. Ding, Z. Huang, J. Krzywinski and A. Lutman
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

Generation of two-pulse two-color x-ray radiation is attracting much attention within the free-electron laser (FEL) user community. Femtosecond and attosecond x-ray pulses with variable duration and separation can be simply generated by the emittance-spoiler foil method at the Linac Coherent Light Source (LCLS). In this paper, we describe and compare three FEL schemes rely on the emittance-spoiler technique for the generation of two intense x-ray pulses with different colors. With a representative realistic set of parameters of LCLS, numerical simulations confirm that femtosecond x-ray pulses at ten gigawatt level at x-ray wavelengths can be generated by these schemes. The central wavelengths of the output pulses can be easily altered by changing strengths of the undulators.

INTRODUCTION

Two-color operation of Free-electron lasers (FELs) at variable wavelengths in the x-ray regime is of considerable interest in recent days. Applications exist over a broad range of wavelengths involving pump-probe experiments, especially the measurement of the evolution of valence electronic wave packets using Stimulated X-ray Raman Spectroscopy (SXRS) [1]. The SXRS generally requires a pair of ultra-short x-ray pulses with different colors. The first x-ray pulse with carrier wavelength tuned on resonance with a given core hole is used to create a valence electronic wave packet localized in the vicinity of a selected atom. This wave packet is later probed by a window localized on a different atom, selected by the second x-ray pulse with different carrier wavelength. All valence electronic states within the pulse bandwidths can be observed with high spatial and temporal resolution by monitoring the variation of the signal with the delay between the pulses. The atom specificity helps to define where the wave packet of valence electrons is created and where it is probed, which simplifies the analysis of the experiment and aids in understanding the spatial distribution of the valence electron wave packets. It has been proposed in Ref [2] that this kind of two attosecond x-ray pulses with different colors can be produced using the same electron bunch by a two stage seeded FEL scheme, which combine the current enhanced self-amplified spontaneous emission and the echo-enabled harmonic generation technique.

The Linac Coherent Light Source (LCLS) has been in operation since 2009 [3]. An emittance-spoiling foil was added later in the middle of the second bunch compressor for generating femtosecond and attosecond intense x-ray radiation pulses with variable duration and separation [4-6]. At soft x-ray regime, almost single-spike pulses can be generated with using the slotted foil setup, as can be seen in the following examples. If the carrier wavelength of each radiation pulse could be separately controlled, this kind of radiation pulses can also be used for the SXRS experiments.

The emittance-spoiling foil method takes advantage of the fact that the SASE gain process is highly sensitive to the transverse slice emittance. 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 beam will be spoiled while leaving only short unspoiled parts to produce x-ray radiation pulses much shorter than the total electron bunch. The central wavelength of each radiation pulse is fixed by the energy of the electron beam γ and the undulator parameter K, and can be written as

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+K^2/2\right), \quad (1)$$

where λ_u is the magnetic period of the undulator and K varies with the undulator gap for the permanent magnet undulators. There are generally two methods that can be used to make the carrier wavelengths of the radiation pulses different: one method is impact an energy chirp on the electron beam to make the central energies of the unspoiled parts of the electron beam different. By using this method, the output wavelengths generated by different parts of the electron beam will be correlated with the separation between the radiation pulses and not easy to separately control. Another method which can be used to overcome this problem is making the electron beam passing through two undulator sections with different undulator parameters, K_1 and K_2, respectively. The output wavelengths of the two pulses can be separately tuned by changing the gaps of the undulators. In this paper, we propose three schemes based on the emittance-spoiler technique and variable gap undulators to generate two-color ultra-short x-ray pulses with variable time delay for user applications such as the SXRS experiment.

METHODS

The layouts of the undulator systems of the three proposed schemes are schematically shown in figure 1. The first two schemes consist of two variable-gap undulator sections separated by a chicane. One may find

ISBN 978-3-95450-123-6

that this beam line is just the widely adopted configuration of the self-seeding scheme [7] (without the grating-based monochromator), which is already exist at the LCLS. An additional chicane can be added between U2 and U3 for the third scheme for further control of the separation between the two output pulses.

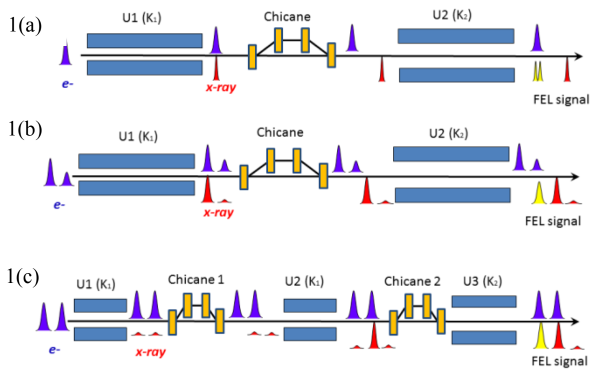

Figure 1: Schematic of three two-color FEL schemes.

For the first scheme shown in figure 1(a), a single slot foil is placed in the second bunch compressor of the linac to generate a short unspoiled part in the electron beam. It is found from the simulation results that the time-sliced emittance distribution is not uniform along the unspoiled part of the electron beam, which will result in different FEL saturation lengths for different electron slices in the undulator sections. By properly setting the length of U1 with undulator parameter K_1, the radiation pulse generated by the central slices of the unspoiled part will reach saturation first with carrier wavelength λ_1, while the radiation power generated by other slices is still quite low. The first radiation pulse is travelling straightforward at the speed of light while the electron-beam is shifted behind relative to the radiation pulse by the chicane and the e-beam micro-bunching developed in U1 will be also washed out at the same time by the momentum compaction of the chicane R_{56}. Sending this electron beam into U2 with K_2, the central slices of the unspoiled beam will not contribute to FEL generation because of the large energy spread, but the side slices still hold the capability to produce powerful radiation pulse with carrier wavelength λ_2 in U2. The separation between the two radiation pulses is arbitrary and can be easily turned by changing the strength of the chicane. The two radiation pulses can also be overlapped with each other by simply turning off the chicane.

For the second scheme, as shown in figure 1(b), a double slot foil is adopted to generate two unspoiled parts in the electron beam. The electron beam is energy chirped by adjusting the phase of the accelerator and then over-compressed by the bunch compressor in the linac to make the peak currents of the two unspoiled parts different. The relative relation between the peak currents of the two unspoiled parts is so chosen to make that the first radiation pulse generated by the high peak current part could reach saturation in U1, while the radiation pulse generated by the low peak current part is still far from saturation at the end of U1. After passing through a second long undulator section U2 with K_2, the second radiation pulse generated by the low peak current part will reach saturation with a different carrier wavelength λ_2. The durations of the radiation pulses are determined by the widths of the slots and can be adjusted according to the requirement. The separation between the two pulses is also arbitrary and can be controlled from zero to a reasonable delay by adjusting either the separation of the slots or the strength of the chicane.

The third proposed scheme consists of three undulator sections and two chicanes, as shown in figure 1(c). A double slot foil is adopted in the linac to generated two unspoiled parts in the electron beam with nearly equal peak currents from e-beam under-compression mode. This electron beam is first sent through a short undulator section U1 with K_1 to generation two radiation pulses with carrier wavelength λ_1 both far from saturation. By properly setting the strength of chicane1 to delay e-beams, the behind radiation pulse is set to overlap with the front unspoiled part of the electron beam and will be amplified by this "fresh bunch" to get saturation in U2, while the radiation pulse generated by the behind unspoiled part, which is unseeded, will be still quite weak after passage through U2. Sending this electron beam into the third undulator section U3 with K_2, a second radiation pulse generated by the behind unspoiled part will reach saturation with a different carrier wavelength λ_2. The minimal separation between the two output pulses is determined by the separation of the slots, which can controlled from about 10fs to about 80fs at the present LCLS. The separation can be further increased by adjusting the strength of chicane2.

SIMULATION

To illustrate the feasibility of generating two-color x-ray pulses using these three schemes, start-to-end simulations with realistic parameters of LCLS have been carried out. The bunch charge is set to be 250 pC. As the required photon energy for the SXRS experiment is around 700eV, the beam energy at the exit of the linac is chosen to be 4GeV. After a two-stage bunch compression, the beam peak current is increased to about 1.5kA in our setup. A slot foil is placed in the second bunch compressor to select small parts of the electron beam for FEL generation. The undulator configurations are the same as that used in LCLS, i.e., the undulator period is 3 cm, there are breaks between each undulator section and the number of undulator period is 110 for each segment (with totally 32 segments available). The electron beam is tracked through the main accelerator with help of ELEGENT [8] taking into account of multiple coulomb scattering in the slotted foil, the CSR and ISR effects in bunch compressors, the linac wakefields, and a model for the transition radiation wakefield of the foil, which will

ISBN 978-3-95450-123-6

significantly increase the emittance and energy spread of the unspoiled beam slices. With the electron beam input from ELEGENT, the FEL performances in the undulators are simulated by GENESIS [9].

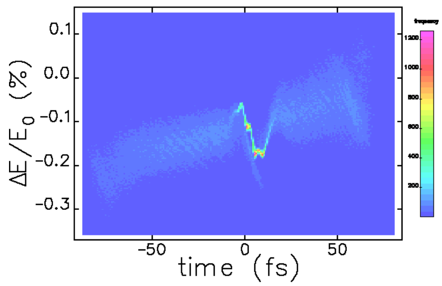

Figure 2: Longitudinal phase space at the exit of the linac.

For the first proposed scheme, a single slot foil with slot width of 0.25mm is used in the simulation. The longitudinal phase space distribution at the exit of the linac is shown in figure 2, from which one can find that most part of the electron beam is spoiled, leaving only a small part of beam unspoiled. The slice energy spread and emittance distributions are not uniform along the

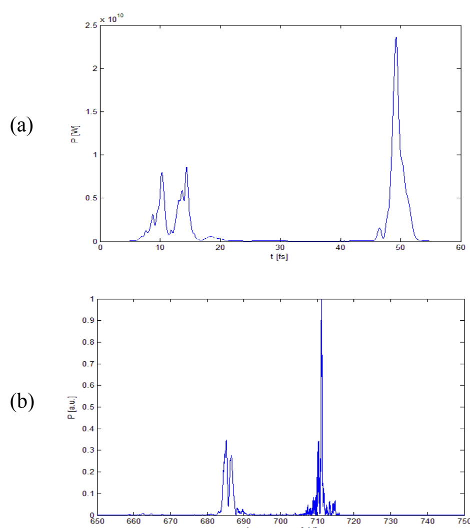

Figure 3: Output radiation pulses (a) and corresponding spectrum (b) generated by the first scheme.

unspoiled part of the electron beam. The undulator lengths for U1 and U2 are chosen to be 7 segments and 13 segments to make the first radiation generated by central slices reach almost saturation in U1 and the second radiation generated by side slices reach saturation in U2. The undulator parameters of the two undulator sections are $K_1 = 3.5$ and $K_2 = 3.43$, which are tuned for FEL resonance at a wavelength of $\lambda_1 = 1.8nm$ (corresponding to an photon energy of 690eV) and $\lambda_2 = 1.74nm$ (photon energy of 714eV). These undulator parameters will also be used for the following simulations for other two cases. The strength of the chicane is set to be $R_{56} = -24\mu m$ to make the separation between the two pulses of about 40fs. The simulation results of the output radiation pulses and the corresponding spectrum are shown in figure 3. These simulation results confirm that the radiation power generated by the central slices of the unspoiled beam growth much faster than side slices and reach saturation at exit of U1 with the output peak power over 20GW. The second radiation pulse is mainly generated by the side parts of the unspoiled electron beam in U2 with output peak power around 10GW.

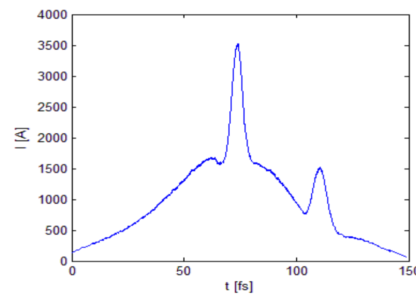

Figure 4: Electron beam current profile for the over-compression case with double-slot foil (bunch head is to the right).

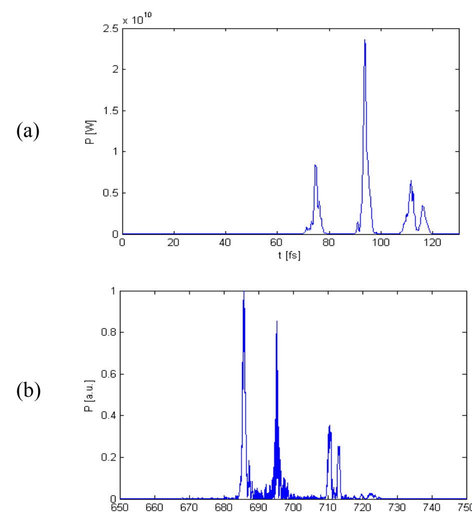

Figure 5: Output radiation pulses (a) and corresponding spectrum (b) generated by the second scheme.

For the second scheme, a double slot foil with slot widths of 0.25mm is used in the simulation. The current distribution along the electron beam at the exit of the linac is shown in figure 4, from which one can find that the separation between the two unspoiled beam is around 40 fs. The peak current of the two unspoiled parts are around 1500A and 500A if only consider the electrons with a good emittance, although it shows much higher currents for these two parts in Fig.5 due to mixing from the emitance-spoiled electrons. The strength of the chicane is set to be $R_{56} = -12\mu m$ to make the separation between the two pulses of about 20 fs in this example (getting closer). We can further increase the chicane strength to make them overlap or to make a larger separation. The simulation results of the output radiation pulses and the corresponding spectrum are shown in figure 5. It is found from figure 5(a) that there are three output pulses. The radiation pulse with high peak power over 20 GW is generated by the high peak current part in U1, while the other two pulses are generated by both the high (side parts) and low peak current parts in U2. As there is an energy chirp in the electron beam, the carrier wavelengths of these three pulses are all different, as figure 5(b) shows.

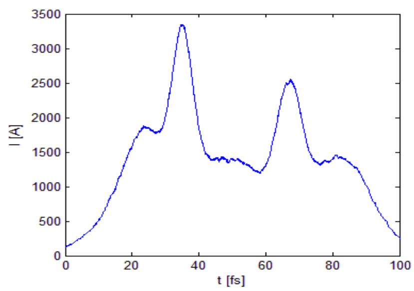

Figure 6: Electron beam current profile for the under-compression case with double-slot foil (bunch head is to the right).

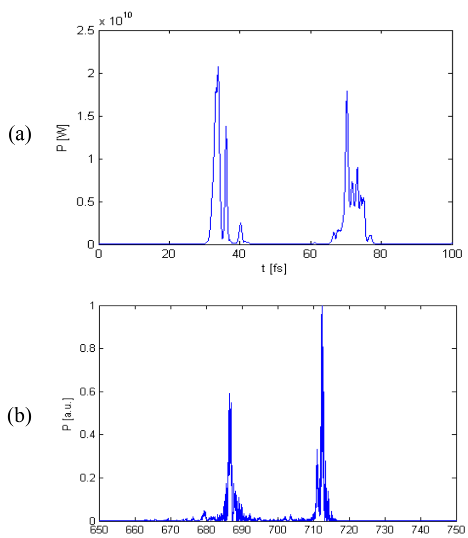

Figure 7: Output radiation pulses (a) and corresponding spectrum (b) generated by the second scheme.

A double slot foil with slot width of 0.4 mm is used in the simulation for the third scheme. The current distribution along the electron beam at the exit of the linac is shown in figure 6, from which one can see that the separation between the two unspoiled beam is around 40 fs, and the peak current of the two parts are nearly the same with an effective current of around 1500A (if only consider the electrons with a good emittance). The strength of the chicane1 is set to be $R_{56} = -24\mu m$ to correlate the front unspoiled beam and the behind radiation pulse generated by U1. The chicane2 is turned off in this simulation. The output radiation pulses and corresponding spectrum are shown in figure 7. The peak powers of the two pulses are all around 20GW. The photon energy of the first radiation pulse is around 710eV and the photon energy of the second radiation pulse is around 690eV.

CONCLUSION

Three two-pulse two-color FEL schemes based on the emittance spoiler technique have been proposed and studied. The first proposed scheme is the simplest way for two-color FEL generation and seems very easy to be carried out at LCLS. However, in a real machine, it is not easy to control to achieve saturation in U1 for the core beam and to obtain a similar intensity in U2 from the the side beams. The second scheme is quite flexible. Both the durations and separation can be controlled by changing the widths of the slots or the strength of the chicane. However, it is found from the simulation results that the unspoiled beam with high peak current will generate powerful radiation pulses both in U1 and U2, together with the low peak current part totally three-color radiation pulses will be generated. The third scheme is the most complex one in configuration but have the best performance. The only problem is that the minimal separation between the two output pulses is limited by the separation of the slots, and adding chicane2 can only further increase the pulse separation. Compared with the two stage seeded FEL scheme, the two radiation pulses generated by the emittance spoiler method have the advantage of natural synchronization even for attosecond pulses (to a certain degree because the energy jitter becomes time jitter after the chicane).

The intensity stability for the different colors is also an important issue for user application, and needs further studies. At the same time, experimental tests have been planned at LCLS using all the three schemes and the results will be reported later.

ACKNOWLEDGEMENTS

The authors want to thank H. Durr, J. Hastings and T. Maxwell for helpful discussions, and thank M. Borland for the help of using Elegant with double-slot foil. This work is supported by Department of Energy Contract No. AC02-76SF00515 and Major State Basic Research Development Program of China (973 Program) (Grant No. 2011CB808300).

REFERENCES

[1] I.V. Schweigert, S. Mukamel, Phys. Rev. A 76, 012504 (2007).
[2] A. Zholents, G. Penn, Nucl. Instr. and Meth. A 612, 254-259 (2010).
[3] P. Emma et al., Nature Photon. 4, 641 (2010).
[4] P. Emma et al., PRL 92, 074801 (2004).
[5] Y. Ding et al., this proceedings, THOC04.
[6] P. Emma, Z. Huang and M. Borland, in Proceedings of the 2004 FEL Conference, 333-338.
[7] J. Feldhaus et al., Opt. Commun. 140,341 (1997).
[8] M. Borland, ANL Advanced Photon Source Report No. LS-287 (2000).
[9] Reiche S, Nucl Instr Meth A, 429, 243−248 (1999).

ISBN 978-3-95450-123-6