DESIGN STUDIES FOR CASCADED HGHG AND EESHG EXPERIMENTS BASED ON SDUV-FEL

C. Feng, M. Zhang, J.H. Chen, H.X. Deng, Q. Gu, D. Wang, Z.T. Zhao
Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China

Abstract

Cascading stages of high-gain harmonic generation (HGHG) free electron laser (FEL) is a promising way to produce fully coherent X-ray radiation. As a test facility for modern FEL R&D, The Shanghai deep ultra-violent FEL (SDUV-FEL) is now under upgrading for the cascading two stage of HGHG experiment. It is found that this upgraded facility will be also well suited for the echo-enabled staged harmonic generation (EESHG) scheme demonstration. With help of 3D simulation codes, design studies on the FEL physics for both these two schemes are present in this paper.

INTRODUCTION

The SDUV FEL is a seeded FEL test facility designed for generating coherent output with wavelength down to the Ultraviolet region. The design and the relevant R&D of this facility have been under way since 2000 [1], and the two-stage cascading HGHG scheme [2] on the basis of this facility have been proposed several years ago [3]. Recently, the HGHG and EEHG experiments have been successfully carried out [4]. The next goal of this facility is to demonstrate the principle of the cascaded HGHG scheme, including the "fresh bunch" technique. Since the energy of the electron beam is as low as about 185MeV after upgrade, the total harmonic number of this two stages HGHG is only 2×2, and the wavelength of the final radiation is 196.5nm which is the 4th harmonic of the 786nm seed laser. These parameters are quite different from the previous design.

Although the primary purpose of the upgrade is to validate the cascading of HGHG stages, it is found that the upgraded scheme is also an ideal platform for the proof-of-principle experiment of the EESHG [5, 6]. The wavelength of the final radiation of EESHG is 450nm which is not any harmonic of the seed lasers: 1047nm and 786nm. So it will be easy to separate the EESHG signal from the cascaded HGHG signal. With help of the analytical estimates and the 3D codes, design studies for both the cascaded HGHG and EESHG schemes based on the upgraded SDUV FEL are present.

LAYOUT

The layout of the upgraded SDUV-FEL is schematically shown in Fig. 1. The upgrade is based on the existing facility. The energy of the electron beam will be enhanced from 140MeV to about 200MeV when there is no bunch compression, and the energy will be about 185MeV when the beam is compressed by a factor of about 2. New elements will be added for the cascaded HGHG experiment, including one radiator (R1) in the 1st stage, one modulator (M3) and one dispersion section (DS3) in the 2nd stage and one shifter between two stages. There are two modulators (M1&M2) in the 1st stage which was designed for the EEHG experiment. Only the M2 will be used for the cascaded HGHG experiment. Main parameters of this upgraded scheme are listed in Table 1.

Table 1: Machine Parameters of the Upgraded SDUV.

$E = 120 \sim 185 MeV$, $I_p = 100A$, $\varepsilon = 1.5 mm \cdot mrad$, $\sigma_\gamma / \gamma = 0.03\%$, $1 \sim 2 ps$ rms length

	Stage 1		Stage 2
Seed laser	1	2	3
$\tau(rms)$	8ps	45fs	~45fs
$\lambda_s(nm)$	1047	786	393~629
Modulator	1	2	3
$\lambda_u(mm)$	65	50	40
B_{peak}(T)	0~1.2	0~1.1	0~0.9
$L_m(m)$	0.65	0.5	0.64
Dispersion section	1	2	3
$R_{56}(mm)$	0~40	0~10	0~10
Radiator	1		2
$\lambda_u(mm)$	40		25
B_{peak}(T)	0~0.9		0.6
$L_r(m)$	4		10

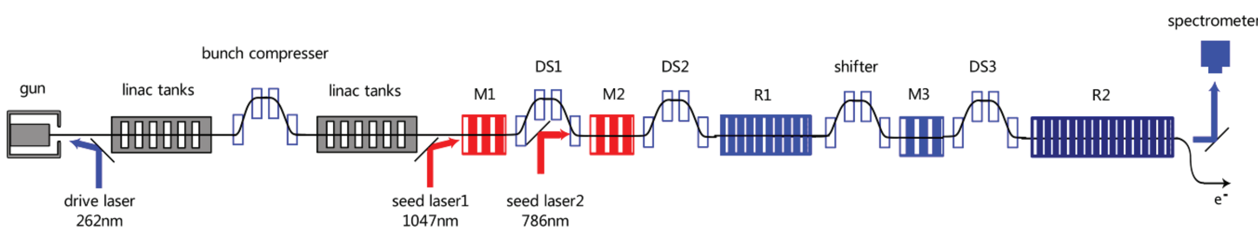

Figure 1: Schematic layout of the upgraded SDUV-FEL.

ISBN 978-3-95450-117-5

CASCADED HGHG

The 1st stage of the cascaded HGHG expects to generate 393nm radiation from the 786nm seed laser. The rms length of the seed laser pulse is only about 45fs which is much shorter than the electron bunch length (1~2ps) after compression. So only part of the electron beam is modulated in M2 and generates coherent radiation in R1. This radiation will be shifted to a fresh part in the electron by the shifter and serves as the seed laser for the 2nd stage. A short undulator with the type of the R1 is employed as the modulator and a small chicane is used as the dispersion section in the 2nd stage. Finally, the 196.5nm radiation will be generated by the fresh bunch in R2.

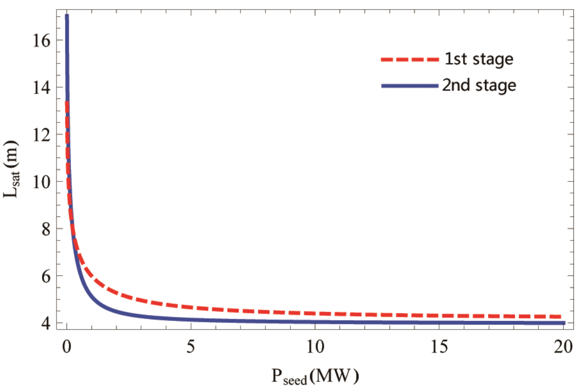

Figure 2: 1st and 2nd stage saturation lengths as a function of the seed laser power of the 1st stage.

In comparison with the SASE scheme, cascaded HGHG is a multi-dimensional parameter scheme. The design and optimization of SDUV cascaded HGHG are achieved by using the HGHG theories given by Yu [7]. According to the HGHG theories, the power of the seed laser and the DS strength are crucial to the HGHG process. A large seed laser power is necessary for sufficient energy modulation, but at the same time it acts as an additional energy spread that degrades the quality of the electron beam. When the total energy spread is too large, the amplification process of the FEL will be saturated. The seed laser of the 2nd stage is produced by the 1st stage, so how to choose the power of the 1st seed laser will be very important. Figure 2 shows the theoretical results of the saturation lengths as a function of the seed laser power for both two stages. It is found that the saturation length of the 2nd stage will not change much when the power of the initial seed laser is larger than 10MW for our experimental condition. Thus, the power of the seed laser is chosen to be 10MW for the first stage.

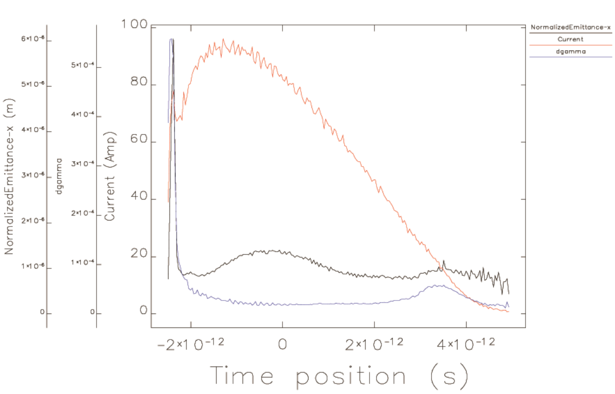

Figure 3: Simulated parameters at the exit of the linac.

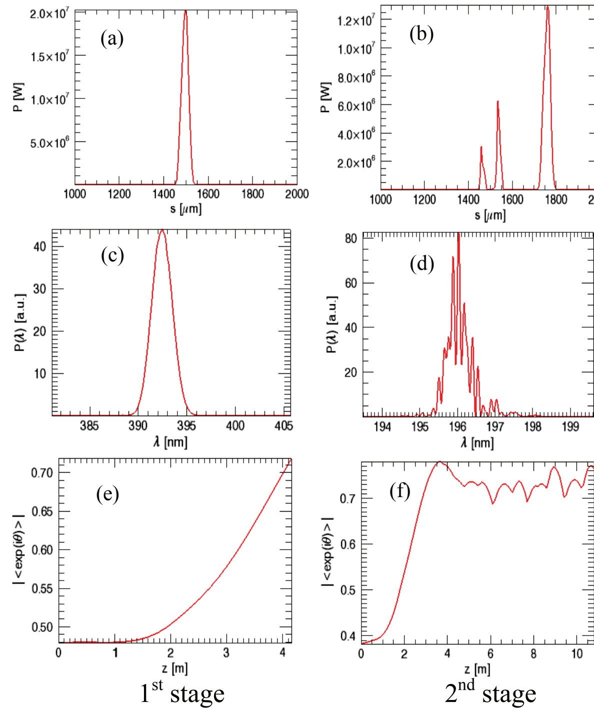

Figure 4: FEL performance of two stages. (a-b) radiation pulse; (c-d) spectrum; (e-f) fundamental bunching factor as a function of the radiator length;

On the basis of the parameters shown in Table 1, start-to-end tracking of the of the electron beam, including all components in Fig. 1, have been completed. The photo injector was simulated with ASTRA [8] to take in to account space-charge effects. ELEGENT [9] was used for the remainder of the linac, while tracking in the undulators was performed with GENESIS [10]. The slice parameters at the exit of the linac are summarized in Fig. 3. A slice emittance of approximately 1.5 πmm mrad and an energy spread of 5 keV is predicted. A constant profile is maintained in the approximately 1ps wide and over 80A region which will be used in the HGHG cascade.

The FEL performance of our cascading scheme was simulated by GENESIS based on the output of ELEGENT. A 786nm seed pulse with longitudinal Gaussian profile, 10MW peak power and 45fs pulse length is used as the seed laser of the 1st stage. To obtain realistic simulation results, the whole electron beam was tracked through the 1st stage to the 2nd stage HGHG. The simulation results are illustrated in Fig. 4. The 1st stage HGHG generates 393nm radiation pulse with the output peak power of about 20MW. The length of the seed laser pulse is maintained. The bunching factor at the entrance

ISBN 978-3-95450-117-5

to the 1st radiator is about 0.48, and this number is increased to about 0.72 at the end of the radiator. For the 2nd stage, the radiation saturates after 4m with a peak power of 13MW. One can find in Fig. 4(b) that there are two 196nm radiation pulses at saturation. The higher one is generated by the fresh part of the electron beam, and the lower one, about 20% of the higher pulse energy, is generated by the disturbed part of the electron beam which has been strongly bunched in the radiator of the 1st stage. It is necessary to change the strength of the shifter to distinguish the 4th harmonic signal produced by the fresh part from that produced by the disturbed part: the final radiation will be produced only by the disturbed part when the shifter is off, and final radiation will be significantly enhanced when the radiation form the 1st stage is shifted to a fresh part of the electron beam. The temporal coherence of the final radiation is degraded by the radiation pulse produced by the disturbed part as shown in Fig. 4(d).

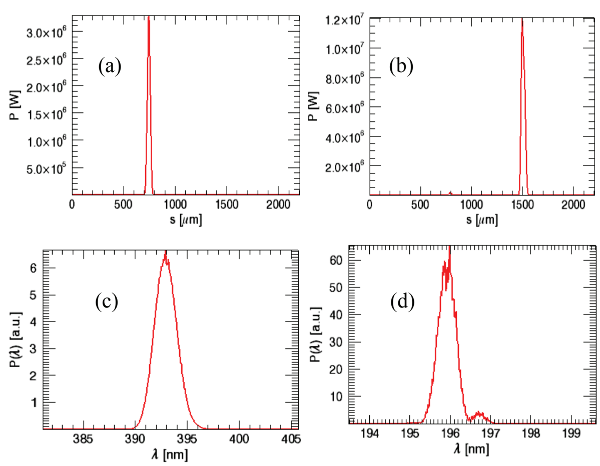

Figure 5: FEL performance. (a-b) radiation pulses; (c-d) spectrum.

The energy of the radiation pulse produced by the disturbed part in R2 can be depressed by shifting the disturbed part to a low-current region of the electron beam. This can be achieved by shifting the initial seed laser pulse to the tail part of the electron beam in M2. The radiation power of the 1st stage HGHG will also decrease at the same time. So the strength of DS3 needs to be increased to optimize the bunching factor of the fresh part in the 2nd stage. We shifted the seed laser pulse by 800μm where the beam current is about 30A. The simulation results are shown in Fig. 5. The output power of the 1st stage decreases to about 3MW, but it is still sufficient for the energy modulation in the 2nd stage. It is found in Fig. 5(b) that only a single pulse is generated by the 2nd stage. The coherent of the final radiation is also improved.

EESHG

The EESHG scheme is not a simple cascaded EEHG but consists of an EEHG and a HGHG like configuration, as Fig. 1 shows. The M1 and DS1 help to obtain separated energy bands all over the whole electron beam. In the M2, a short seed laser pulse is adopted to modulate only a small part of the electron beam. The energy modulation in this small part will be converted to density modulation by DS2. The radiation produced by the 1st EEHG stage is also shifted to a fresh part of the electron beam by the shifter and serves as the seed laser for the 2nd stage. Noticing that the fresh part has already been modulated and shredded to energy bands in the 1st stage, the 2nd stage will also works in the EEHG principle.

The main parameters of the EESHG scheme based on SDUV-FEL are present in Table. 2. According to the basic theory of EEHG and EESHG the output frequency of the 1st stage and 2nd stage can be written as

$$\omega_{E1} = n\omega_{s1} + m\omega_{s2} \tag{1}$$

$$\omega_{E2} = (pn+q)\omega_{s1} + pm\omega_{s2}\,, \tag{2}$$

Where ω_{s1} and ω_{s2} are the frequencies of the seed lasers in the 1st stage. n, m, p and q are integer numbers. For our experiment, we chose $n=-1$, $m=2$, $p=-1$ and $q=2$. The wavelengths of the seed lasers are different: the seed laser in M1 is 1047nm and in M2 is 786nm. So the output wavelengths of the 1st and 2nd stages are 629nm and 450nm. The required beam energy is only 120MeV.

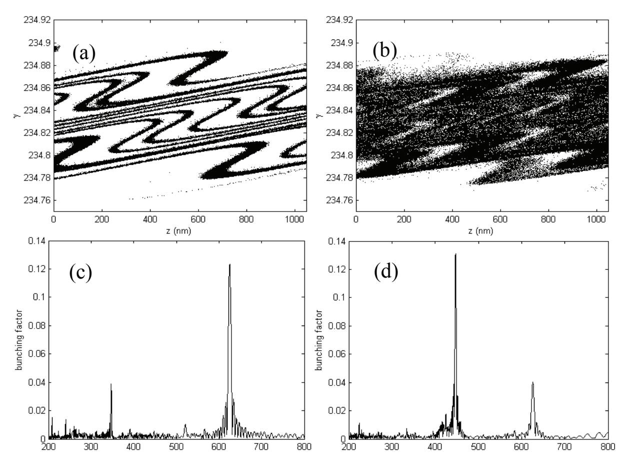

Figure 6: phase space (a) and corresponding bunching factor (c) of the part of the electron beam used in the 1st stage after DS2; phase space (b) and corresponding bunching factor (d) of the fresh part of the electron beam used in the 2nd stage after DS3.

A self-consistent FEL simulation code is employed to study the performance of our EESHG scheme by the time-dependent simulation. The simulation results are shown in Figs. 6, 7. From Fig. 6 it is possible to appreciate the effect of EEHG on the electron beam phase

ISBN 978-3-95450-117-5

space at the entrances to the radiators of both stages. The vertical stripes in Fig. 6 (a-b) are responsible of the density modulation of the beam charge, whose Fourier components are shown in Fig. 6 (c-d). The bunching factor of the part of the beam used in the 1st stage is about 0.12 at 629nm, and there is no bunching at 450nm. The quantum diffusion in the R1 does have some smearing effect on the fine structures, but with proper design of the lattice, one can still get sufficient bunching of about 0.13 at 450nm in the fresh part after DS3.

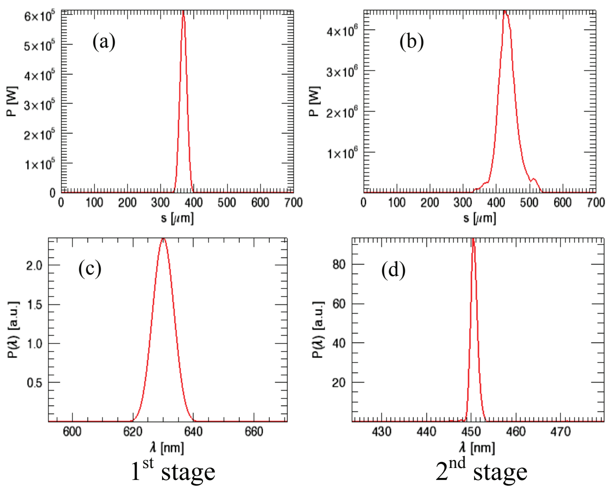

Figure 7: FEL performance of EESHG. (a-b) radiation pulses; (c-d) spectrum.

Figure 7 illustrate the FEL performance of the EESHG. The peak output power of the 1st stage is about 0.6MW which serves as the seed laser in the 2nd stage. As the disturbed part has no bunching at 450nm, there is only a single pulse in the R2. The final radiation power is over 4MW. The bandwidths are very close to the Fourier transform limit.

CONCLUSION

In conclusion, we present design studies of cascaded HGHG and EESHG based on the upgraded SDUV-FEL. The results show that with an additional stage of HGHG, the proof-of-principle experiments of cascaded HGHG and EESHG can be carried out at our facility. The radiation of the cascaded HGHG at 196.5nm will reach saturation in the 2nd stage. The signal of the EESHG at 450nm can be obtain by properly choosing the parameters of the machine. The upgrade of SDUV will be finished in July and the commissioning of cascaded HGHG will be started in August.

ACKNOWLEDGEMENTS

This work is supported by National Natural Science Foundation of China (Grant No. 10935011) and Major State Basic Research Development Program of China (973 Program) (Grant No. 2011CB808300).

REFERENCES

[1] Z.T. Zhao, *et al*. Nucl Instr Meth A, 528, 591 (2004).
[2] J.H. Wu, L.H. Yu. Nucl Instr Meth A, 475, 102 (2001).
[3] H.X. Deng, Z.M. Dai. Chinese Physics C, 32, 236-242 (2008).
[4] Z.T. Zhao, in Proceedings of FEL 2011, Shanghai, WEOBI2.
[5] C. Feng, Z.T. Zhao. Chinese Sci Bull, 55, 221-227 (2010).
[6] D. Xiang, et al, in Proceedings of FEL 09, Liverpool.
[7] L.H. Yu, J.H. Wu. Nucl Instr Meth A, 483, 493 (2002).
[8] K. Floettmann, ASTRA User's Manual.
[9] M. Borland, ANL Advanced Photon Source Report No. LS-287, 2000.
[10] Reiche S, Nucl Instr Meth A, 429, 243−248 (1999).

ISBN 978-3-95450-117-5