OPERATING THE SDUV-FEL WITH THE EEHG SCHEME*

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Abstract

Using the recently proposed echo-enabled harmonic generation (EEHG) free-electron laser (FEL) scheme, it is shown that operating the Shanghai deep ultraviolet FEL (SDUV-FEL) with single-stage to higher harmonics is very promising, with higher frequency up-conversion efficiency, higher harmonic selectivity and lower power requirement of the seed laser. The considerations on a proof-of-principle experiment and expected performance in SDUV-FEL are given.

INTRODUCTION

The Shanghai deep ultraviolet FEL (SDUV-FEL) [1, 2] is an HGHG FEL user facility designed for generating coherent output with wavelength down to deep ultraviolet region, which is currently under construction.

It is well know that microbunching plays an essential role in the FEL process. In recent years, there is a growing interest in improving the up-frequency conversion efficiency, and a number of double modulator schemes are proposed [3], among which the echo-enabled harmonic generation (EEHG) scheme has unprecedented up-frequency conversion efficiency and allows for generation of ultrahigh harmonic with a relatively smaller energy modulation [4, 5].

It is found that SDUV-FEL is well suited for the EEHG scheme with only minor modifications needed [6]. In this paper, operating the SDUV-FEL with the EEHG scheme is explored and the plan for proof-of-principle experiments is described with expected performance outlined.

SDUV-FEL WITH EEHG SCHEME

EEHG Principle

In contrast to the conventional high-gain harmonic generation (HGHG) FEL scheme [7-9], the EEHG FEL scheme is composed of two modulators, two dispersive sections (DS) and a radiator, as shown in Figure 1. The frequencies of the first and second modulators can be different. The first DS is chosen such that the energy modulation induced in the first modulator is macroscopically smeared out. At the same time, this smearing introduces a complicated fine structure into the phase space of the beam. The echo then occurs as a recoherence effect caused by the mixing of the correlations between the modulation in the second modulator and the structures imprinted onto the phase space by the combined effect of the first modulator and the first DS.

For a practical case, with equal wavelength for both modulators, the bunching factor for the k-th harmonics reads [4, 5],

$$b_k = 2\left|\sum_{m=-\infty}^{\infty} e^{im\phi} J_{-m-k}(A_1((m+k)B_1+kB_2)) \times J_m(kA_2B_2)\, e^{-\frac{1}{2}((m+k)B_1+kB_2)^2}\right|$$

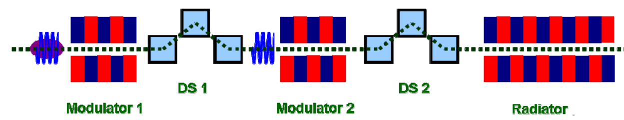

Figure 1: Schematic view of EEHG FEL.

As an example, we show that the 24th harmonics of the seed laser can be generated with small energy modulation with dimensionless parameters:

$A_1 = 3,\ A_2 = 1,\ B_1 = 26.8,\ B_2 = 1.14$.

The longitudinal phase space evolution in the EEHG FEL scheme is shown in Figure 2.

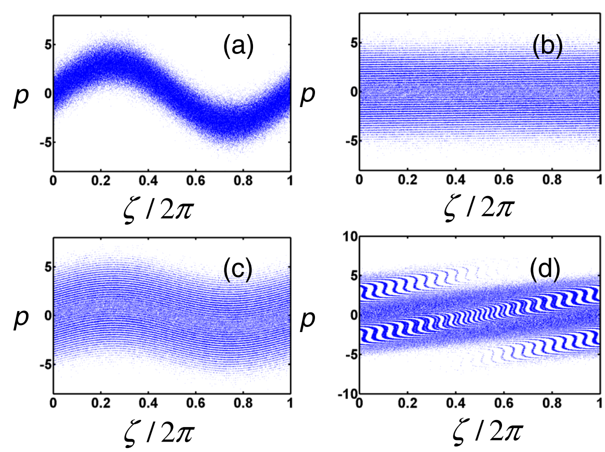

Figure 2: Longitudinal phase space evolution: (a) after the first modulator; (b) after the first DS; (c) after the second modulator; and (d) after the second DS.

It is shown, in Figure 3, that the 24th bunching factor remains within 10% deviation from 0.2 to 0.22 (relativity much higher than the conventional HGHG FEL scheme) even with 1% B_1 and/or B_2 deviation.

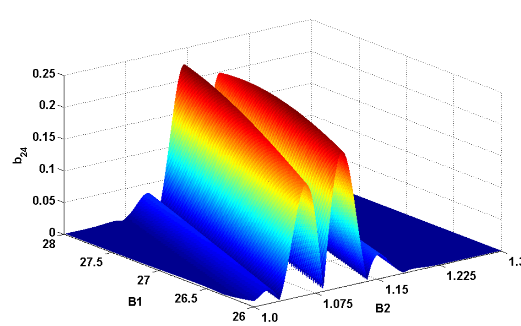

Figure 3: Bunching factor sensitivity vs. DS parameters.

Modifications to the SDUV-FEL

With necessary modifications to the original design, it is possible to operate the SDUV-FEL with EEHG scheme, as shown in Figure 4. Another modulator is added. The original laser injection chicane is redesigned to produce larger R_{56}. The seed laser is split into two beams for the two modulators. One more laser injection port is added near the linac exit.

In order to well demonstrate and characterize the EEHG scheme in comparison with the conventional HGHG scheme, it is determined to first operate both schemes in the same harmonics, i.e., the 4th harmonics of seed laser.

The main machine parameters for SDUV-FEL with EEHG scheme are shown in Table 1. The parameter of Seed Laser 2 is identical to Seed Laser 1 and Modulator 2 identical to Modulator 1

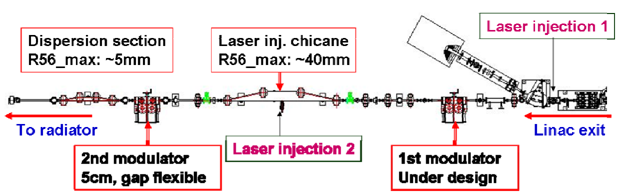

Figure 4: Layout of the double-modulator section of SDUV-FEL with EEHG scheme.

Table 1 Machine parameters for SDUV-FEL with EEHG scheme.

Electron beam	
Beam energy	160MeV
Slice energy spread (rms)	32keV
Normalized emittance	5mm.mrad
Length (rms)	2~3ps
Seed Laser 1	
Wavelength	1047nm
Pulse length	8ps
Peak power	2MW
Modulator 1	
Period length	5cm
Number of periods	10
K	2.49
Dispersive section 1	
Total length	2m
R_{56}	6.011mm
Dispersive section 2	
Total length	1m
R_{56}	1.316mm
Radiator	
Period length	2.5cm
Length/Segment	1.5m
Number of segments	6
K	1.45

PERFORMANCE SIMULATION

In the previous sections, the analysis is based on simple one-dimensional assumption. However in practice three-dimensional effects should be taken into account, which includes coupling of transverse and longitudinal degrees of freedom, finite laser spot size, incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR) in DS, and many others. The expected performance under these circumferences is evaluated by intensive simulations with elegant [10] and GENESIS [11, 12].

With the parameters listed in Table 1, and seed laser with peak power 2MW and waist radius of 1mm, the longitudinal phase space after the two stages of energy modulation and density modulation process is shown in Figure 5, where the 4th harmonic pre-bunching before entering radiator is clearly displayed.

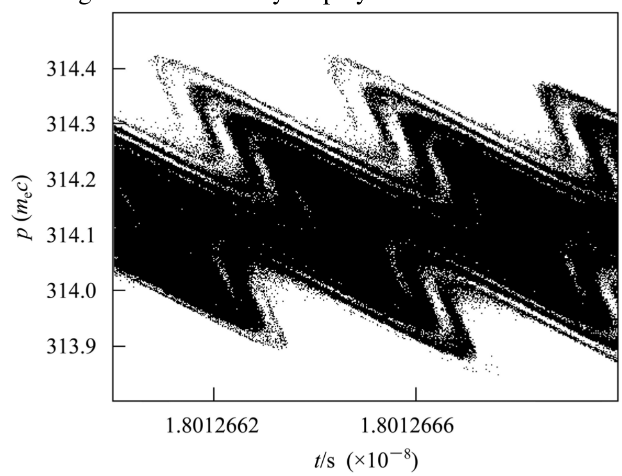

Figure 5: Longitudinal phase space after DS2 (simulation with elegant).

The FEL simulation is performed with the upgraded code GENESIS [12] which consists of three parts of runs. In the first run, the energy modulation from the 1047 nm seed laser in the first modulator is simulated and the particle distribution is dumped at the exit of Modulator 1. The particle distribution is imported, transported through DS 1 and further sent to Modulator 2 for the other energy modulation. At the exit of Modulator 2, the particle distribution is dumped again. Finally, the particle distribution is re-imported for the third run and the undulator period of the radiator is tuned to the 4th harmonic of the seed laser, i.e. 262nm. The significant enhancement of SDUV-FEL with EEHG scheme is clearly seen in Figure 6 and Figure 7, where the peak power of the 4th harmonic exceeds 100MW and the power saturates very quickly within 4m. The large bunching factor favored by EEHG is responsible for the initial steep quadratic growth of power. Both advantages are attributed to the large initial bunching factor and small energy modulation. In addition, the energy spread increasing is also relatively small compared to the conventional HGHG FEL scheme. Time-dependent simulation is also performed with GENESIS, and radiation spectrum is shown in Figure 8.

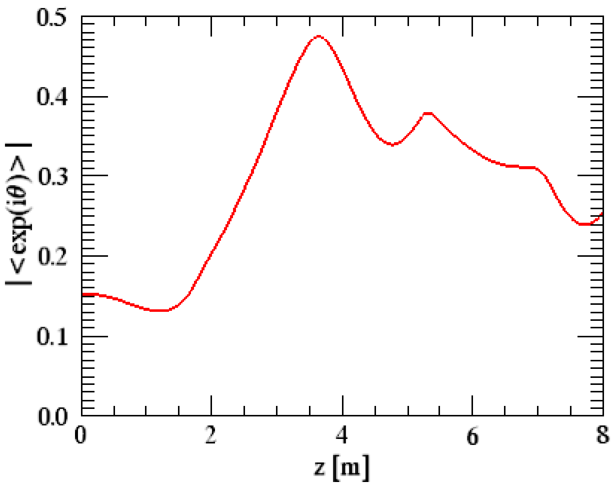

Figure 6: Bunching factor evolution.

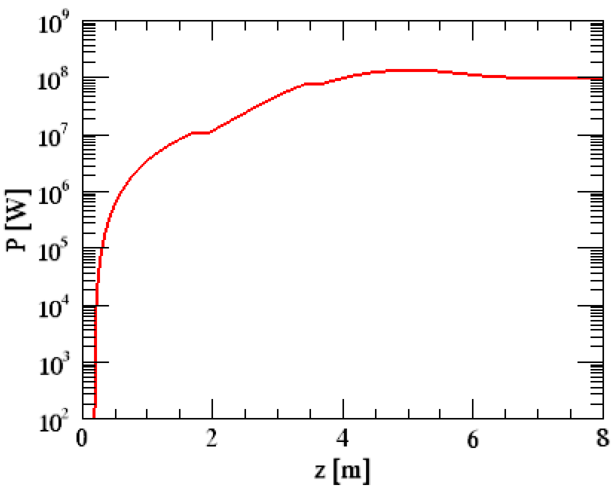

Figure 7: Radiation power growth.

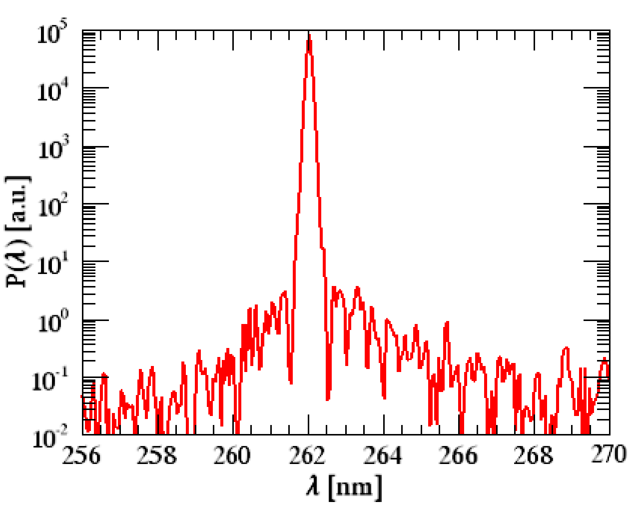

Figure 8: Radiation spectrum from SDUV-FEL with EEHG scheme.

CONCLUSION

The feasibility of operating SDUV-FEL with EEHG scheme is presented. It is shown that the EEHG has a great potential as it allows for generating short wavelength radiation with much higher harmonics in single stage of harmonic generation FEL, therefore it may potentially reduce the number of stages of cascaded HGHG.

It is worth stressing that this study is preliminary and there is still room for further improvement. It should also be noticed that several effects such as incoherent and coherent synchrotron radiation existed in the DS, which may induce diffusion process; longitudinal electron beam profile and so on, are not included in this study.

Constrained with the electron beam energy and radiator undulator period, SDUV-FEL can current be operated with lower harmonics, 4th harmonic for instance as depicted in this paper. However, in order to fully explore the potential capabilities of EEHG scheme, running the SDUV-FEL with higher harmonics, 24th for instance, are also envisioned and spare parameter room are reserved. Diagnostics of microbunching structure with coherent radiation from pre-bunched beam after DS2 is under serious consideration.

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