# PRE-DENSITY MODULATION OF THE ELECTRON BEAM FOR SOFT X-RAY FEL IN THE WATER WINDOW*

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*Abstract*

The high-gain seeded free-electron laser (FEL) schemes are capable of producing fully coherent radiation in the short wavelength regions. In this paper, we introduce the pre-density modulation (PDM) scheme to enhance the performance of the echo-enabled harmonic generation (EEHG) scheme and to significantly extend the short-wavelength range. The PDM is used to enhance the microbunching and reduce the electron energy spread of seeded FEL schemes by gathering most of the electron into the phase range which makes a contribution to the microbunching.

## INTRODUCTION

High-gain seeded FEL schemes have been developed for producing stable and fully temporal coherence laser pulse. High-gain harmonic generation (HGHG) scheme [1] is a promising candidate for short wavelength FEL, but the wavelength conversion efficiency of one-stage HGHG becomes very low for very high harmonics due to the large energy modulation required and shot noise degradation[2, 3]. Therefore, whether HGHG FEL could reach x-ray region is still a hot issue discussed for many years.

Recently, some novel double-modulator schemes such as silence scheme [4], enhanced HGHG (EHGHG) scheme [5] and echo-enabled harmonic generation (EEHG) scheme [6] have been put forward to enhance the bunching factor of higher harmonics for one-stage HG-FEL. In these schemes, silence scheme and EHGHG focus on suppressing the extra energy spread by a violent seed laser and a $\pi$ phase shifter between two modulators. EEHG using the beam echo effect to maximize the bunching factor for a specific harmonic number. Analytical calculations and simulations imply that single-stage silence scheme, EHGHG and EEHG are all capable to generate high power soft X-ray radiation from a UV seed laser [4, 5, 7], but EEHG shows its unique status due to producing large bunching factor at high harmonics with small energy spread.

In this paper, a pre-density modulation (PDM) scheme is proposed to enhance the bunching factor of EEHG scheme.

## PRINCIPLE

EEHG scheme is composed of two modulators, two dispersion sections and a radiator. The electron beam is energy modulated in the first modulator and then sent through a very strong dispersion section, which makes the energy modulation induced in the first modulator macroscopically smeared out, but in the phase space of the e-beam, many small pieces along the longitudinal direction appear. The e-beam with this energy bands structure will be modulated again in the second modulator by another laser beam. After passing through the second dispersion section, the separated energy bands will be converted to the separated current bands which will introduce a maximal bunching factor at very high harmonics when adjusting the power of the seeding lasers and the dispersive strength of each magnetic chicane.

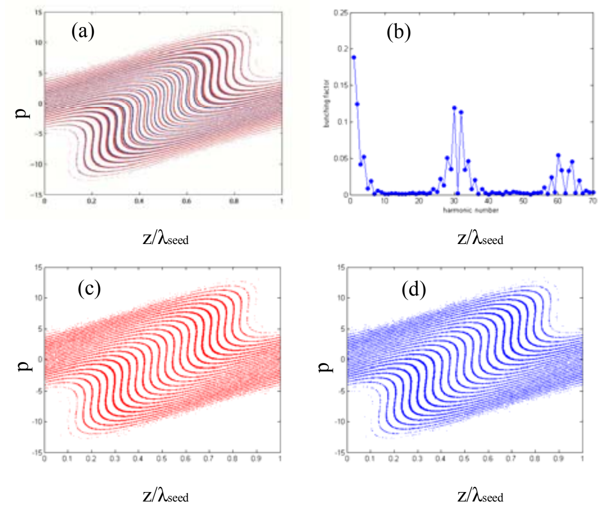


Figure 1: Physical mechanism of EEHG (a) longitudinal phase space at the entrance to the radiator, which is mixed with red part (c) and blue part (d); (b) bunching factor versus harmonic numbers of the seed laser.

One feature of EEHG is that there are always two maximum values of bunching factor around the target radiation wavelength. A one-dimensional simulation is used here to show the physical mechanism behind this appearance. With the frequencies of two seed lasers equal $\omega_1 = \omega_2$, we optimize parameters of an EEHG to maximize the bunching factor at 30th harmonic following the method in Ref. [7]. The longitudinal phase space at the entrance to the radiator is shown in figure. 1 (a) and the bunching factors at various harmonic numbers of this structure are shown in figure. 1 (b), besides the 30th harmonic, another maximum value at 32nd harmonic is also appearing. The reason for this appearance is that the current distribution at the exit of the send dispersion section is mixed with two bunching structures at different harmonics. The complicated bunching structure of EEHG like figure. 1 (a) shows can be divided into two uniform bunching structures as figure. 1 (c) & (d) show, which indicate a presence of the 30th and 32nd harmonics of the initial seed laser.

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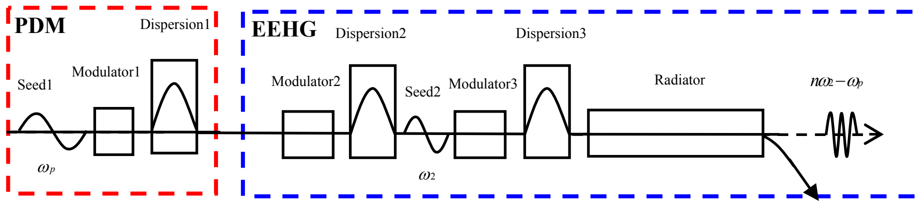


Figure 2: Schematic of the PDM enhanced HGHG and PDM enhanced EEHG.

We propose the PDM scheme to enhance the bunching factor of the target harmonic and eliminate the other one. The schematic of the PDM enhanced EEHG scheme are shown in figure. 2. PDM is consists of one short undulator and one chicane, which are similar to the modulator and dispersion section in classic HGHG. Figure. 3 shows the physics processes of PDM. First the electron beam is energy modulated through a very short undulator by a seed laser (figure. 3 (b)), the resonant

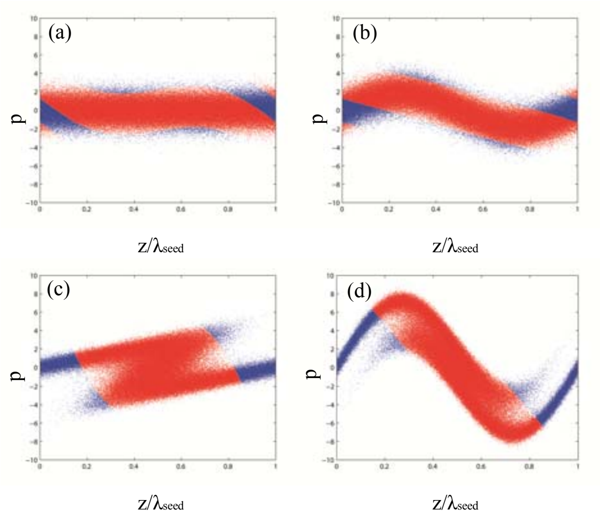


Figure 3: Longitudinal phase space evolution in the PDM scheme, the red electrons make a contribution to the microbunching. (a) Phase space at the entrance to modulator; (b) Phase space after the undulator in PDM; (c) Phase space at the exist of PDM; (d) Phase space at the exist of the following modulator;

wavelength of this undulator should be proximity to the 1st modulator of the following seeded FEL scheme. Then a small chicane is used for over-bunching the electron beam like figure. 3 (c) shows. This overbunching is aiming at gathering most of the electronics in the phase range of $-\pi/2$ to $\pi/2$ of the fundamental optical field, which is useful for the microbunching. Then this pre-density modulated beam can be send into EEHG. Since the microbunching is already formed after PDM, the electron beam will release violent coherent radiation at fundamental wavelength when it passing through the first modulator of EEHG, and the electron beam will be modulated by its own radiation. From figure. 2. one can find that there is no need for a seed laser in the 1$^{st}$ modulator of EEHG. When properly choosing the resonant wavelength of this modulator, the fine structure in the phase space as figure. 3 (d) shows can be generated. The following processes are similar to EEHG. The phase space at the entrance to the radiator is shown in figure. 4 (a) shows and the bunching factor at various harmonic numbers is shown in figure. 4. (b)

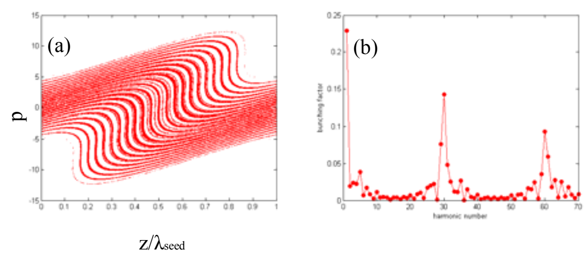


Figure 4: Enhance the bunching factor of EEHG by a PDM (a) longitudinal phase space at the entrance to the radiator; (b) bunching factor versus harmonic numbers of the seed laser.

Using a one-dimensional model of HG-FEL we can deduce the nth bunching factor after the 2$^{nd}$ dispersion section in the PDM enhanced EEHG scheme,

$$
\begin{aligned}
b_n = \Bigg| & \sum_{n_1=-\infty}^{\infty}\sum_{n_2=-\infty}^{\infty} J_{n_2}\{-A_1[(n_1+kn_2)B_1+(n_1+kn_2+k'n_3)B_2]\} \\
& \times J_{n_3}[-A_2(n_1+kn_2+k'n_3)B_2] \\
& \times J_{n_1}\{-A_p[n_1B_p+(n_1+kn_2)B_1+(n_1+kn_2+k'n_3)B_2]\} \\
& \times e^{-1/2[n_1B_p+(n_1+kn_2)B_1+(n_1+kn_2+k'n_3)B_2]^2} \Bigg|
\end{aligned}
\tag{1}
$$

Here $n_1, n_2$ and $n_3$ are integer numbers, the harmonic number $A_p, A_1, A_2$ are dimensionless amplitude of beam energy in the undulator of PDM and double modulators in EEHG, $B_p, B_1, B_2$ are the scale parameters of the chicane strength in PDM and EEHG, $k=\omega_p/\omega_1=1$, $\omega_p$ is the frequency of the seed laser in PDM and $k'=\omega_1/\omega_2$. This function is complicated for analytical maximization of $b_n$, analysis shows that for the PDM enhanced EEHG scheme function (2) can simplify as the following form when $k'=1$

$$
\begin{aligned}
b_n \approx \Bigg| & \sum_{n_2=-2}^{2} J_{n_2}[-A_1(-B_1+nB_2)]J_{n+1}(-A_2nB_2) \\
& \times J_{-n_2-1}\{-A_p[(-n_2-1)B_p-B_1+nB_2]\}e^{-1/2[(-n_2-1)B_p-B_1+nB_2]^2} \Bigg|
\end{aligned}
\tag{2}
$$

for given amplitude of the modulation $A_p, A_1, A_2$, to maximize the absolute value of the nth bunching factor $b_n$, one should first optimize the chicane strength parameter $B_p$ and $B_2$ by maximize the value of the function $J_1(A_pB_p)e^{-(1/2)[B_p]^2}$ and $J_{n+1}(-A_2nB_2)$, then $B_1$ can be optimized by maximize the absolute value of function (2).

## EXAMPLE

In order to obtain soft X-ray in the "water window", Shanghai soft X-ray Free electron laser (SXFEL) project is designed to generate 4 nm soft X-ray radiation with 1.3GeV electron beam based on SASE scheme. With the normalized beam parameters of SXFEL, We study the feasibility of using only one stage of EEHG to generate coherent soft X-ray radiation at the wavelength lower than 4nm with the help of PDM. The optimization is conducted using GENESIS [8] and the paremeters are summarized in Table 1.

Table 1: Machine parameters for SXFEL with the PDM enhanced EEHG scheme.

| Electron bunch | | | |
|---|---|---|---|
| $E=1.3GeV, I_p=600A, \varepsilon=2mm\cdot mrad$, $\sigma_\gamma/\gamma=0.1\sim0.15\%$, $1.6ps$ length | | | |
| | PDM | EEHG | |
| Seed laser | | 1 | 2 |
| $\lambda_s(nm)$ | 240 | / | 240 |
| Modulator | | 1 | 2 |
| $\lambda_u(cm)$ | 5.8 | 5.8 | 5.8 |
| $a_u$ | 7.25 | 7.4 | 7.25 |
| $L_m(m)$ | 0.24 | 1.0 | 1.0 |
| Dispersion section | | 1 | 2 |
| $R_{56}(mm)$ | 0.6 | 6.9 | 0.22 |
| Radiator | | | |
| $\lambda_u(cm)$ | 2.6 | | |
| $a_u$ | 0.995 | | |
| $L_r(m)$ | 30 | | |
| $\lambda_{sr}(nm)$ | 3.9 | | |

The evolution of radiation power along the radiator is shown in figure. 5, the peak power of the 3.9nm radiation exceeds 240MW and it saturates at about 25m. Compare with the existing EEHG scheme, the saturation power is 2 times higher and the saturation length is 1.6 times shorter.

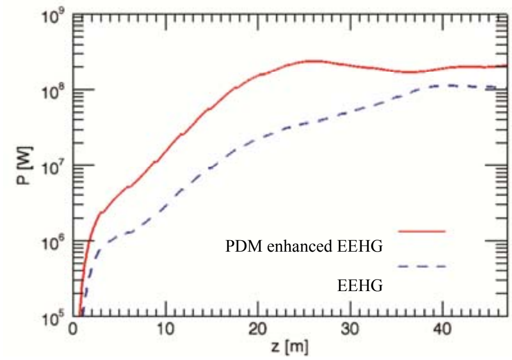


Figure 5: The peak power evolution of 3.9nm radiation along the radiator of EEHG (blue) and PDM enhanced EEHG (red).

## CONCLUSION

PDM consists of one short undulator and one chicane. It can significantly enhance the bunching factor of seeded FEL schemes and reduces the additional energy spread at the same time. Since the microbunching is already formed after PDM, the electron beam will be modulated by its own radiation in the following modulator and there is no need for an additional seed laser. 3D simulation results show that PDM can enhance the performance of EEHG and it is possible to generate powerful soft X-ray radiation in the water window directly from a 240nm seed laser with realistic beam parameters.

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## REFERENCES

[1] YU L. H, Phys. Rev. A, 44 (1991), 5178.
[2] Saldin E L, Schneidmiller E A, Yurkov M Y, Opt. Commun. 202 (2002), 169.
[3] HUANG Z. Proceedings FEL Conference 2006.
[4] E. Allaria and G. De Ninno, Phys. Rev. Lett, 99 (2007), 014801.
[5] Q. Jia, Appl. Phys. Lett, 93 (2008), 141102.
[6] G. Stupakov, Phys. Rev. Lett, 102 (2009), 074801.
[7] D. Xiang and G. Stupakov, Phys. Rev. STAB, 12 (2009), 030702.
[8] S. Reiche, Nucl. Instr. and Meth A, 429 (1999), 243.