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GENRATIONG ULTRASHORT X-RAY PULSE IN A DIFFRACTION-LIMED STORAGE RING BY PHASE-MERGING ENHACED HARMONIC GENERATION WITH NORMAL MODULATOR*

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Abstract

In recent years, the study of ultrafast processes has increased the demand for ultrashort pulses. The duration of the synchrotron radiation pulse is generally in the range of 10-100 ps, which cannot be used in the experiments of studying the ultrafast process. Thus it is interesting to explore a way of obtaining sub-picosecond radiation pulses in storage ring light sources. The phase-merging enhanced harmonic generation (PEHG) scheme using a transverse gradient undulator as the modulator can be used to generate coherent radiation at high harmonic, which is very suitable for the generating ultrashort pulses in a diffraction-limed storage ring (DLSR). This paper presents a new PEHG modulation scheme, using a normal undulator as the modulator. This scheme is technically easier to be realized in a DLSR. Simulation is performed to demonstrate the effectiveness of this method.

INTRODUCTION

The phase-merging enhanced harmonic generation (PEHG)[1, 2], as shown in Fig. 2(a), using a transverse gradient undulator (TGU) as the energy modulator, has been proposed for the seeded free electron lasers (FELs). To implement PEHG in a diffraction-limed storage ring (DLSR) without significantly disturbing the optics and the ring performance, it is necessary to meet some restrictions, i.e. the dispersion function η cannot be too large (e.g. η<10 cm), and the energy modulation should be small enough (e.g. lower than the initial energy spread). Under these conditions we find the TGU gradient parameter α should be not less than 100 m^{-1}. Fig. 1 shows the value of α at different cant angle ϕ for the cases with different magnetic fields. One can see that to realize an α of about 100 m^{-1}, a high magnetic field and a big cant angle are required, which are difficult (if not impossible) to be realized in practice.

Recently, two other schemes are proposed to achieve the phase-merging effect without the TGU. One scheme is to use a modified dogleg, a normal short modulator and a modified chicane [3]. And the other is to use the natural field gradient of a normal undulator in the vertical direction [4]. In this paper, we propose an alternative, simple and easy-to-implement scheme to generate the phase-merging effect. As shown in Fig. 2(b) this scheme adopts a dipole at the exit of a normal undulator to replace the function of TGU. We take a DLSR, the Hefei Advanced Light Source (HALS) as an example to demonstrate the feasibility of this scheme.

Diffusion mechanisms that may affect the micro-bunching structure, such as the Coulomb collisions and quantum diffusion due to the incoherent synchrotron radiation (ISR) are considered.

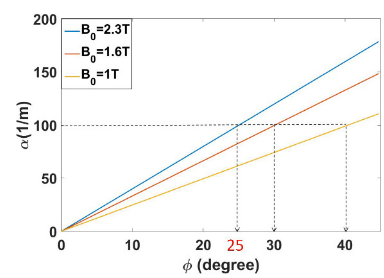

Figure 1: Variations of the TGU gradient parameter α with cant angle for the cases with different peak magnetic field.

METHOD

The layout of the proposed scheme is illustrated in Fig. 2(b).

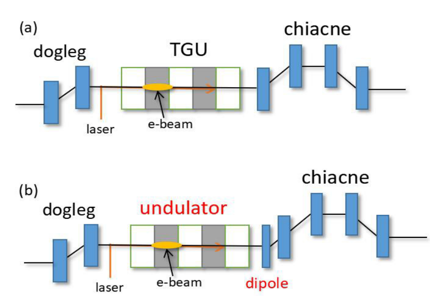

Figure 2: PEHG scheme based on TGU (a), and the proposed scheme (b).

The 4-by-4 linear matrix in the *x-z* plane is adopted to explain the principle of this scheme. The phase space coordinates are (x, x', z, δ).

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The dogleg transport matrix is

$$R_{dogleg} = \begin{bmatrix} 1 & L_D & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & r_d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where L_D is the length of the dogleg, η and r_d are the transverse and longitudinal dispersion, respectively.

The approximate transport matrix of the modulator can be expressed as [5]

$$R_{Moud} = \begin{bmatrix} 1 & L_M & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & h & 1 \end{bmatrix} \quad (2)$$

where $h=k_L\Delta\gamma/\gamma$ is the the energy chirp, k_L is the wave number of the seed wavelength and $\Delta\gamma/\gamma$ is the amplitude of the energy modulation.

The transport matrix of a short dipole (kicker) with bending angle b is

$$R_{dipole} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -b \\ b & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The transport matrix of a four-bend chicane is

$$R_{chicane} = \begin{bmatrix} 1 & L_c & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & r_c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where r_c is the longitudinal dispersion.

The transform matrix of the whole beam line shown in Fig. 1(b) is

$$R = R_{chicane} \cdot R_{dipole} \cdot R_{Moud} \cdot R_{dogleg} \quad (5)$$

When $1+hr_c=0$ and $b\eta+r_c=0$, the R matrix reduces to

$$R = \begin{bmatrix} 1 & L-bL_c h\eta & -bhL_c & \eta - bL_c(1+hr_d) \\ 0 & 1-bh\eta & -bh & -b(1+hr_d) \\ b & b(L_D+L_M) & 0 & 0 \\ 0 & h\eta & h & 1+hr_d \end{bmatrix} \quad (6)$$

where $L=L_c+L_D+L_M$.

Following the derivations in Ref.[2], we obtain the expression of the bunching factor at nth harmonic

$$b_n = J_n(nk_L r_c \frac{\Delta\gamma}{\gamma}) e^{\frac{-(k_L bn)^2}{2}(\sigma_x{}^2+(l\sigma_{x'})^2)} \quad (7)$$

where $l=L_D+L_M$, and the effect of the intrinsic beam divergence is take into account.

The exponential suppression factor in the bunching factor formula: Eq.(7), depends on the harmonic number, the intrinsic beam size and beam divergence. At high harmonic, the bunching factor will be reduced exponentially. Since this exponential suppression factor also depends on the emittance, a smaller emittance can result in a higher bunching factor. Thus, one can predict higher harmonic radiation when adopting PEHG in a DLSR rather than a third generation light source.

SIMULATION

Taking the HALS [6] as an example, we evaluate the radiation performance with the PEHG scheme. The seed scheme is aimed to generate 4 nm radiation ultrashort pulses. To make full use of the advantages of the small emittance of the DLSR, the dispersion and the dipole bending direction is chosen to be in vertical plane. The mean parameters are listed in Table 1.

The simulation results at the exit of the chicane are presented in Fig. 3 and 4. The bunching factors at various harmonic numbers are shown in Fig. 4. As the harmonic number becomes larger, the bunching factor is decreased. In order to generate 4 nm radiation, the harmonic number is chosen to 60, and the corresponding bunching factor is 0.075.

The bunched electrons are tracked though a 1.8 m long undulator to generate coherent radiation. The simulation results are shown in Fig. 5. With the help of a 30 fs length (FWHM) seed laser and the proposed scheme, we obtain a 11.2 fs length (FWHM) radiation pulse with peak power about 3 kW, and the spectral bandwidth of about 0.06% (FWHM).

Table 1: Mean Parameters for PEHG Scheme.

Parameters	Values
Beam energy	2 GeV
Peak current	12 A
Emittance (H/V)	142.78/7.14 pm
Energy spread	2.82 MeV
Dogleg dispersion	8.5 cm
Laser wavelength	240 nm
Energy modulation	2.24 MeV
Dipole bending angle	0.391 mrad
Chicane R56	33.4 μm

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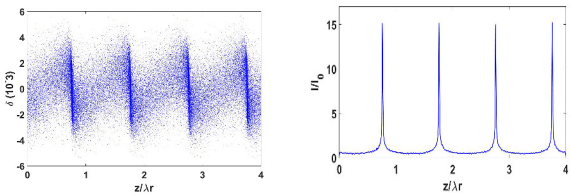

Figure 3: Longitudinal phase space distribution at the exits of the chicane (left) and the corresponding current distribution (right).

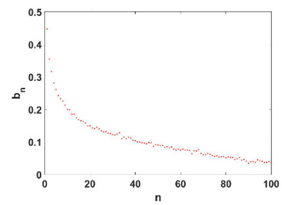

Figure 4: Bunching factor at different harmonic number.

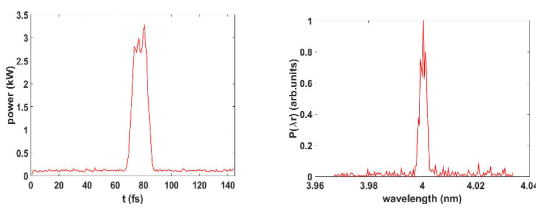

Figure 5: Distributions of the radiation output in time domain (left) and spectrum domain (right) .

COULOMB COLLISIONS AND QUANTUM DIFFUSION ANAIYSIS

At high harmonic, the Coulomb collisions between the particles of the beam (i.e intra-beam scattering, in short IBS) and the quantum diffusion induced by ISR may reduce the bunching factor [7, 8].

In this study, the harmonic number is 60, which is much larger compered to the normal situation [1]. To be self-consistent, we analyse the bunching factor reduced by those diffusion effects.

Following the method proposed in [7], the suppression factor induced by IBS is

$$C_{IBS} = \exp[-\frac{1}{2}(\int_0^L D(z)k_{\Delta E}(z)^2 dz)] \quad (8)$$

The diffusion coefficient D is

$$D(z) = \frac{\Lambda\sqrt{\pi}}{2\gamma\sqrt{\sigma_{x'}(z)\sigma_{y'}(z)}}\frac{(mc^2)^2 r_e}{\sigma_x(z)\sigma_y(z)}\frac{I}{I_A} \quad (9)$$

where I is the peak current, I_A= 17 kA, r_e the classical electron radius and Λ is the Coulomb logarithm.

The energy modulation wave number $k^2{}_{\Delta E}$, can be calculated by R_{56} element of the beam line [8] (see, Fig. 6).

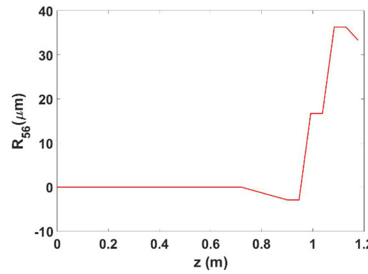

Figure 6: $R_{56}(z)$ from modulator to chicane.

From Eq.(9), the evolution of D from modulator to chicane is calculated and shown in Fig. 7. Compare to the FEL case (D~6 keV^2/m), due to the lower peak current, D is much smaller than 1 in this study. The product $k^2{}_{\Delta E}D$ is shown in Fig.8. Integration of this product through the beam line gives the suppression factor C_{IBS} of ~1.

The suppression factor induced by ISR can be estimated according to the analysis in [8]:

$$C_{ISR} = \exp[-k^2\int_0^L DR^2{}_{56}(z)dz] \quad (10)$$

where k is the wave number of the radiation light. Using the design parameters listed in Table 1, we obtain C_{ISR}=0.9974.

Combining the suppression factors, we find the final bunching factor is $C_{ISR}\times C_{IBS}\times 0.075$~0.0748, only reduced by about 0.26%, which is negligible.

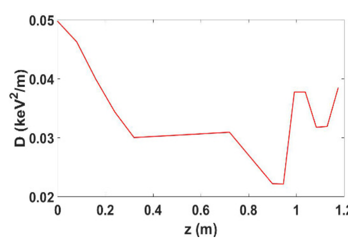

Figure 7: Diffusion coefficient as a function of z.

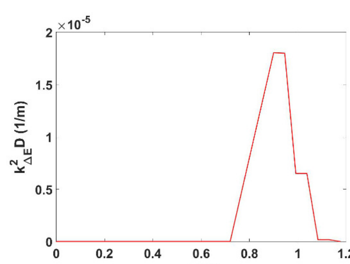

Figure 8: $k^2{}_{\Delta E}D$ as a function of z.

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CONCLUSION

We proposed a new method to generate the phase-merging effect. Numerical and analytical studies suggest that it can be used to generate a water window waveband ultrashort coherent radiation in a DLSR. Benefit from the low peak current in a DLSR, the intra-beam scattering, and quantum diffusion effects that may reduce the bunching factor are negligible.

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REFERENCES

[1] H. Deng, and C. Feng, "Using Off-Resonance Laser Modulation for Beam-Energy-Spread Cooling in Generation of Short-Wavelength Radiation", *Phys. Rev. Lett.* Vol 111, no 8, p. 084801, August 2018.

[2] C. Feng, H. Deng, D. Wang and Z. Zhao, "Phase-merging Enhanced Harmonic Generation Free-electron Laser", *New J. of Phys.* Vol 16, no 4, p. 043021, April 2014.

[3] H. Li, Q. Jia, and Z. Zhao, "Generation of high harmonic free electron laser with phase-merging effect", *Nucl. Instr. and Meth. A* Vol 847, pp. 42-46, 2017.

[4] Z. Zhao, H. Li and Q. Jia, "Phase-merging enhanced harmonic generation free-electron laser with a normal modulator", *J. Synchrotron Rad.* Vol 24, pp. 906-911, July 2017.

[5] Z. Qi, *et al.*, "Parameter optimization and start-to-end simulation for the phase-merging enhanced harmonic generation free electron laser", *Nucl. Instr. And Meth. A* Vol 875, pp. 119-124, December 2017.

[6] N. Hu, *et al.*, "Estimates of Collective Effects in the HALS Storage Ring Having the First Version Lattice", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3770-3773.

[7] G. Stupakov, "Effect of coulomb collisions on echo enabled harmonic generation", in *Proc. FEL'13*, New York, USA, August 2013, p. 684.

[8] N. Yampolsky, *et al.*, "Beam debunching due to ISR-induced energy diffusion", *Nucl. Instr. And Meth. A* Vol 870, pp. 156-162, October 2017.