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Harmonics suppression effect of the quasi-periodic undulator in SASE free-electron-laser

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Abstract: In this paper, the harmonics suppression effect of quasi-periodic undulators (QPUs) in self-amplified spontaneous emission free-electron laser (SASE FEL) is investigated. The numerical results show that the harmonics power is reduced by using QPUs, but the fundamental radiation power also has a pronounced decrease as the saturation length gets very long. The cases of employing QPUs as parts of undulators are studied. The calculations show that if the fraction of QPUs and their offgap are appropriate in an undulator system, the harmonics radiation could be suppressed remarkably, meanwhile the fundamental saturation length does not increase too much.

Key words: quasi-periodic undulator, high harmonics, suppression, SASE FEL

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1 Introduction

The radiation spectrum of the conventional undulator which has periodic magnetic structure is mixed with the fundamental and high order harmonics. For some accelerator users' experiments, high harmonics suppression is very important, thus the first quasi-periodic undulator (QPU) was proposed by Hashimoto and Sasaki [1], in which the magnets are arrayed in the way of the Fibonacci sequence with two irrationally different interpole distances. The typical Halbach QPU was built and tested in ESRF [2] with the H-magnets in quasi-periodic location displaced vertically. Recently two novel schemes of QPU are proposed and the radiation spectral fluxes demonstrate that the new schemes could greatly suppress the high-order harmonic radiation compared with the current QPU [3].

Ordinarily, the QPUs are used as insertion devices in accelerators. Therefore only the spontaneous radiation spectrum is studied in the above research. Actually, the pure monochromatic light is also welcomed by FEL users. In this paper, the suppression effect of a QPU in self-amplified spontaneous emission free-electron laser (SASE FEL) is intensively studied, and compared with that of standard undulator. The numerical simulation of the undulator magnetic fields, spontaneous radiation spectrum and radiation power of SASE FEL have been carried out using the RADIA code [4], the SPECTRA code [5], and GENESIS [6], respectively.

2 The spontaneous radiation spectrum of a QPU

The conventional QPU structure is selected here. The magnetic structure of the QPU is determined as the Fibonacci sequence. Fig. 1 shows the QPU configuration and the main parameters of the undulator are summarized in Table 1. The main parameters are based on the preliminary design research of the VUV-FEL. The electron energy, peak current, energy spread, and emittance are assumed to be 405.2 MeV, 500 A, 0.01%, and 1.9 mm·mrad, respectively.

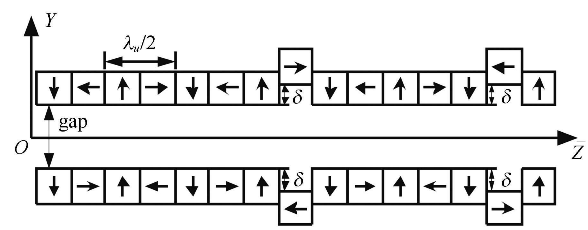

Fig. 1. The QPU configuration.

Table 1. Main parameters of the undulator.

period length/mm	32
period number	50
gap/mm	10
remanence of magnet blocks/T	1.21
height of magnetic blocks/mm	52
width of magnetic blocks/mm	8
offgap (δ)/mm	3/5

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The angular spectral flux densities on axis (10 m from the source) from different undulators are calculated and the results are presented in Fig. 2. It can be found that the 1^{st} radiation of two QPUs (offgap=3 mm and offgap=5 mm) is lower than that of the normal case. But the advantage is that the 3^{rd} and 5^{th} harmonic radiations of QPU (offgap=3 mm) are suppressed by about 22.6% and 13.4%, respectively. For the QPU (offgap=5 mm), the suppression ratios are 24.5% and 20.8%. As a larger offgap is chosen, the high-order harmonics will be suppressed much more efficiently.

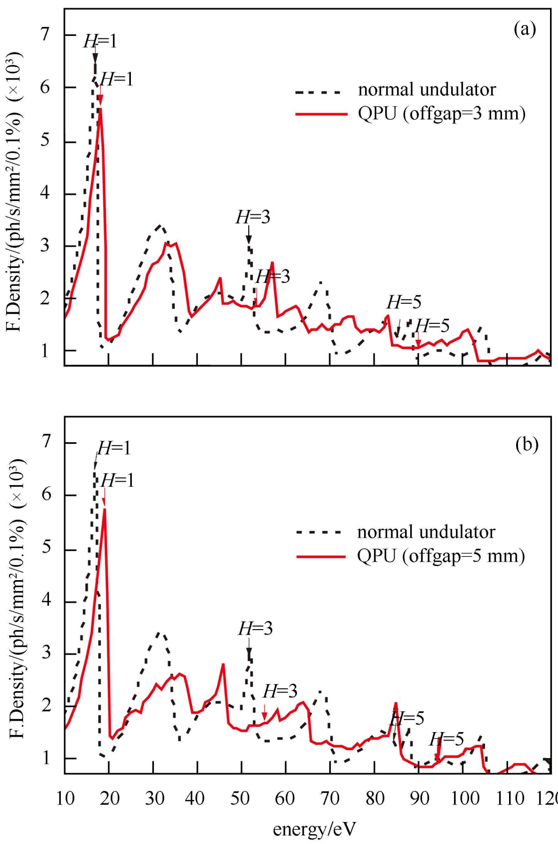

Fig. 2. (color online) The angular spectral flux densities of the standard undulator compared with those of the QPU: (a) offgap=3 mm and (b) offgap=5 mm. The 1^{st}, 3^{rd} and 5^{th} harmonic positions are marked with arrows (the solid ones are for the QPU).

3 The radiation power of SASE FEL

From the spontaneous radiation spectrum mentioned above, the energy of fundamental radiation becomes larger with the increase of offgap. Similarly, the results of a numerical scan indicate that the resonant wavelength of SASE FEL will decrease if we choose a big value of the offgap of the QPUs. Therefore, the calculation of SASE FEL with different undulators must adopt a specific resonant wavelength in the following section. When the offgap rises from 3 mm to 5 mm, the resonant wavelength reduces from 65.6 nm to 64.4 nm.

In this paper, the SASE FEL scheme employs ten undulator sections. First, the SASE FEL process based on ten normal undulators is simulated. The resonant wavelength is 70 nm. The saturated power of the 1^{st} radiation is about 313.5 MW while the power of the 3^{rd} and 5^{th} harmonics is 7.2 MW and 46.3 kW, respectively. The simulation based on ten QPUs with different offgaps is also done, but the results show that the SASE FEL could not start up as the saturation length gets too long. It should be pointed out that the position of the power given in this paper is the end of the entire undulator system and the total length of the undulator system is fixed.

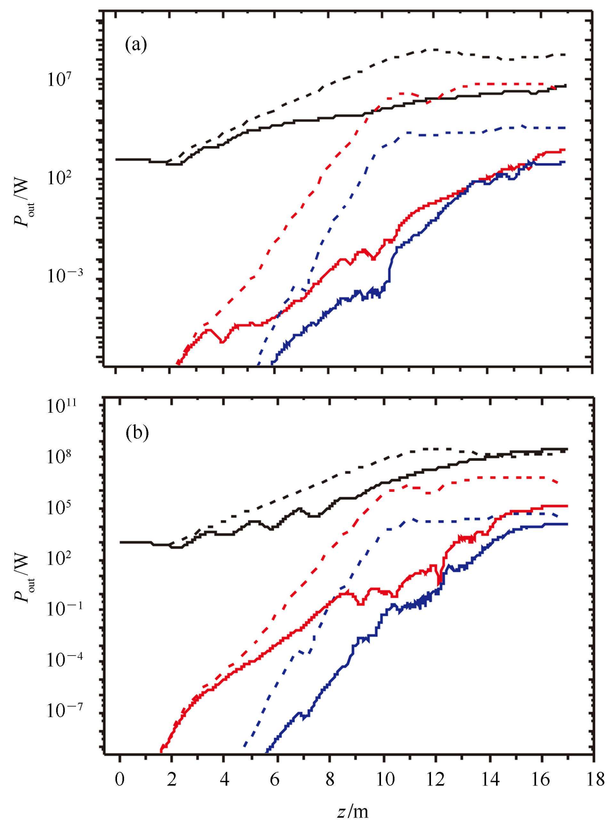

Fig. 3. (color online) The 1^{st} (black lines), 3^{rd} (red lines) and 5^{th} (blue lines) radiation power as a function of the length of undulators. The dashed lines stand for the FEL scheme which employs ten normal undulators; the solid lines stand for the FEL scheme employs: (a) two normal undulators and eight QPUs whose offgap is 5 mm and (b) five normal undulators and five QPUs whose offgap is 5 mm.

In order to shorten the saturation length and guarantee a certain power of the 1^{st} radiation while keeping harmonics radiation suppressed, we considered a combined SASE FEL structure. Using several normal undulators in the front to start up the SASE process and followed by several QPUs to suppress the radiation of the 3rd and 5th harmonics. The corresponding radiation spectrum of this structure is calculated and analyzed. The saturated power of the 1st radiation grows to about 192 MW when using two normal undulators and eight QPUs with the offgap of 3 mm. However, unlike the spontaneous radiation spectrum of a QPU, the growth ratios of the 3rd and 5th harmonics power are about 5% and 0.8% compared with the SASE FEL using ten normal undulators mentioned above. Although the power of the 1st radiation in this structure is considerable, it is not able to revitalize to suppress the high-order harmonics radiation. Fig. 3(a) presents the radiation power as a function of the length of undulators. The dashed lines and solid lines stand for the SASE FEL using ten normal undulators, two normal undulators, and eight QPUs whose offgap is 5 mm, respectively. It can be found that the 3rd (red lines) and 5th (blue lines) harmonics radiations get a noticeable suppression, but the saturation length is still too long and the 1st radiation (black lines) is about 307.8 MW which is lower than that of SASE FEL based on ten normal undualtors.

In the SASE FEL based on five normal undulators and five QPUs, if the offgap of QPUs is 3 mm, the saturated power of the 1st radiation is about 198.8 MW, however, the suppression effect of high-order harmonics is still unfavorable. For the sake of comparison, the radiation power of SASE FEL which includes ten normal undulators (dashed lines) or five normal undulators and five QPUs whose offgap is 5 mm (solid lines) is shown in Fig. 3(b). The black lines, red lines, and blue lines stand for the power of the 1st, 3rd, and 5th radiations, respectively. Although the SASE FEL using five normal undulators and five QPUs could not achieve saturation, the power of the 1st radiation is 333.8 MW, a little higher than that of the conventional scheme. Moreover, the saturated power of the 3rd radiation is about 98% which is lower than that of the common SASE FEL. The saturated power of the 5th radiation is not as low as the 3rd radiation, but it is still much (72%) lower than that of the SASE FEL using ten normal undulators. Even at the original saturated point, the suppressive effect of high-order harmonics is also especially attractive.

4 Conclusions

In conclusion, we have investigated the harmonics suppressive effect of a QPU in SASE FEL. The simulation results from RADIA and GENESIS indicate that the harmonics radiation could be reduced when the normal undualtors are replaced by the QPUs. However, the fundamental radiation power is also very low since the saturation length of SASE FEL becomes quite long. Then we study the SASE FEL process in which the QPUs replace parts of the undualtor system. We find that for an appropriate combination of the normal undulators and QPUs with a proper value of offgap, the harmonics radiation could be suppressed notably. Especially the power of the 3rd radiation is about 98% lower than that of the SASE FEL with normal undulators, at the same time the saturation length does not increase too much.

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