ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-WEP056

EFFECT OF BEAM TRANSVERSE ANGLE DEFLECTION IN TGU ON FEL POWER

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Abstract

Recent study shows that electron beams with constant dispersion together with the transverse-gradient undulator (TGU) can reduce the sensitivity to energy spread for free-electron laser (FEL). By inducing dispersion function, electrons with different energy are placed at different positions corresponding to proper magnetic fields. Thus, FEL resonant condition can be kept for electrons with different energy. In this paper, we mainly studied: 1. The effects of electron beam angle deflection at the entrance of the TGU on the radiation power. 2. The utility of a kicker to introduce an angle deflection of electron beam to improve the FEL radiation power.

INTRODUCTION

Free-electron lasers (FELs) greatly benefit fundamental research in physics, chemistry, materials science, biology, and medicine by producing intense tunable radiation ranging from the infrared to hard x-ray region [1]. However, the FEL facilities are usually large and costly. Efforts have been made to develop compact FELs with similar radiation properties but smaller size. One optional way is to use laser-plasma accelerators (LPAs) to drive a high-gain FEL instead of conventional linear accelerator (LINAC) [2].

Compared to traditional LINAC, LPAs have much higher accelerating field gradient, smaller size and less cost but lager electron beam energy spread. At present, LPA can produce high energy (~ 1 GeV), high peak current (~ 10 kA), and low emittance (~ 0.1 μm) electron beam with a relatively large energy spread about 1% experimentally [3, 4]. Such a relatively large energy spread, compared to conventional LINAC, terribly interferes the FEL gain process, which hinders LPAs from driving a high-gain FEL, which can be understood from the FEL resonance condition,

$$\lambda_r = \frac{1+K_0^2/2}{2\gamma^2}\lambda_u, \quad (1)$$

where K_0=0.934λ_u[cm]B[T], λ_u is the undulator period, B is the peak field of the undulator, γ is the electron beam energy in unit of the rest energy. Energy spread would lead to a spread of the above equation, leading to a weak radiation power adverse to diffraction imaging experiments [5]. To overcome the impediment caused by electron beam energy spread in the FEL gain process, approaches, such as transverse gradient undulator (TGU) [6] and decompression [7], have been proposed and studied in detail. Recent study on TGU for high-gain FEL driven by LPAs points out that electron beam with a proper dispersion cooperating with TGU would increase the output radiation power significantly, about two orders, more effective than decompression [2].

TGU was proposed to reduce the sensitivity to the electron beam energy spread [2, 6]. By canting the magnetic poles, a linear transverse dependence of undulator field can be generated, like

$$\frac{\Delta K}{K} = \alpha x, \quad (2)$$

where α is the transverse gradient of the undulator. For an electron beam dispersed horizontally according to its energy, we get $x=\eta_0\delta$, where η_0 is the electron beam dispersion. Properly choosing the dispersion

$$\eta_0 = \frac{2+K_0^2}{\alpha K_0^2}, \quad (3)$$

and keeping it constant along the TGU, the spread in electron beam's energy would be compensated. Note that, in this paper, we only consider the electron beam dispersed in x direction.

In this paper, we study the effect of beam transverse angle deflection on radiation power. We first analyse the case that the electron beam has an angle deflection at the entrance of TGU. Numerical simulation scan has been done to further quantitatively study the power decrease caused by angle deflection. Then, we study the case that the angle deflection induced at proper position in TGU. By comparing this case with linear tapered undulator, we find that it is possible to make use of angle deflection to improve the radiation power simply with an additional kicker. Multi-dimension optimization has been done and we find that the radiation power improves significantly. Simulations are done based on GENESIS, a 3D FEL simulation software, presenting reliable FEL process, proved by experiments [8].

* The work was supported by the US Dependent of Energy (DOE) under contract DE-AC02-76SF00515 and the US DOE Office of Science Early career Research Program grant FWP-2013-SLAC-100164
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BEAM ANGLE DEFLECTION VERSUS RADIATION POWER

In this section, we investigate the sensitivity of radiation power to transverse angle deflection at the entrance of TGU. Since the electron beam is dispersed in x direction, it is expected that TGU-FEL is more sensitive to angle deflection in x direction.

TGU-FEL makes use of beam dispersion to distribute the electrons with different energy along x direction so that together with TGU the off-resonance electrons could satisfy the resonance condition. And the key is to match the electrons with different energy to proper *K*. Therefore, TGU-FEL is sensitive to angle deflection at the entrance of TGU. Supposing that, the electron beam enters TGU with a small transverse velocity v_x ($v_x << v_z$), which means that the electron beam deviate from its designed trajectory, which is illustrated in Fig. 1. We find that with the electron beam traveling along the TGU, the transverse offset has a linear increase, shown as below,

$$x = \frac{v_x}{v_z} z = \tan\theta_x z \approx \theta_x z \qquad (4)$$

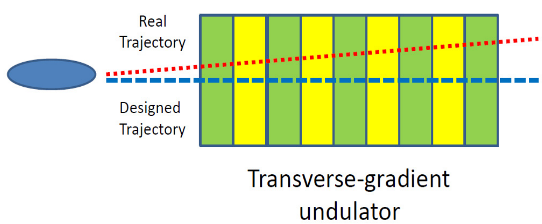

Figure 1: Schematic illustration for beam angle deflection at the entrance of TGU.

From Eqs. (1-3), we can obtain that

$$\frac{1+K_0^2/2}{(1+\rho)^2} < 1 + K_0^2(1+\frac{\alpha v_x}{v_z}z)^2/2 < \frac{1+K_0^2/2}{(1-\rho)^2} \qquad (5)$$

Thus, when v_x is large enough, with the electron beam traveling along the TGU, the electron beam will be out of the gain bandwidth. To further investigate this phenomenon, we did numerical simulation using GENESIS (steady state) with parameters shown in Table 1, listed as below,

Table 1: Parameters for Numerical Simulation

Parameter	Value
Beam energy	500 MeV
Norm. transv. Emittance	0.1 q m
Peak current	5000 A
Rel. rms energy spread	2 %
Undulator period	2 cm
Undulator parameter	1.93
Undulator length	10.0 m
Resonant wavelength	30 nm
Transverse gradient	43 m^{-1}

By scanning the angle deflection in x and y direction, we obtain simulation results shown in Fig. 2, which indicates that the radiation power of TGU-FEL is much more sensitive to u x. Roughly, in our case, tolerance for θ_y is 0.1 mrad but for θ_x is 0.01 mrad.

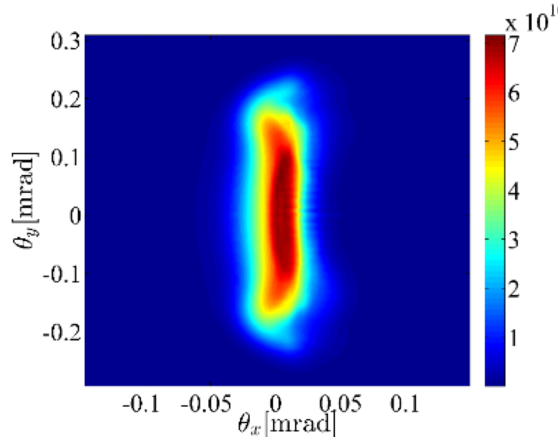

Figure 2: Radiation power as a function of (angle deflection in x direction) and u y (angle deflection in y direction).

ANGLE DEFLECTION AND POWER IMPROVEMENT

In the last section, we find that electron beam angle deflection at the entrance of TGU would lead to radiation power decrease. However, if we use a kicker to induce an angle deflection at a proper position in the TGU, we can even improve the radiation power of TGU-FEL. It is expected to perform like a linear tapered undulator. From Eq. (2) and Eq. (4), we can obtain that,

$$K(z) = K_0(1+\frac{\alpha v_x}{v_z} z) \qquad (6)$$

which is quite similar to the form of a tapered undulator,

$$K(z) = K_0(1+\frac{k}{L} z) \qquad (7)$$

where *k* is the taper ratio, *L* is the length of the tapered part.

Furthermore, we did optimization for TGU-FEL with kicker and without kicker via numerical simulation. Basic parameters are the same as those in Table 1. Considered Twiss parameter, detune, kicker location and kicker strength (induced angle deflection), we have done multi-dimension optimization with GENESIS steady-state simulation and the result is shown in Table 2. The optimizer is robust conjugate direction search (RCDS), a both efficient and robust optimization algorithm [9].

From the optimization result, we can find that the radiation power increases significantly (more than two times) with a kicker added and the electron beam centre transverse offset at end of the undulator would not influence too much (much smaller than the width of pipe). We also have done time-dependent simulation with the

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optimized parameters in Table 2 and the temporal radiation profiles are plotted in Fig. 3. The max power in the radiation pulse almost doubled and the pulse energy increases more than two times.

Table 2: The Optimization Result for TGU with/without Kicker

Parameter	Without kicker	With kicker
Kicker location	-	4.72 m
Angle deflection θ_x	-	0.1732 mrad
Twiss α_x	3.093	2.992
Twiss α_y	-0.064	-0.359
RMS beam size σ_x	49.41 μm	32.68
RMS beam size σ_y	15.94 μm	12.46
K/K_0	0.995	0.999
Detune P	7.00 GW	18.37 GW
Offset Δx	-0.62 μm	-0.89 μm

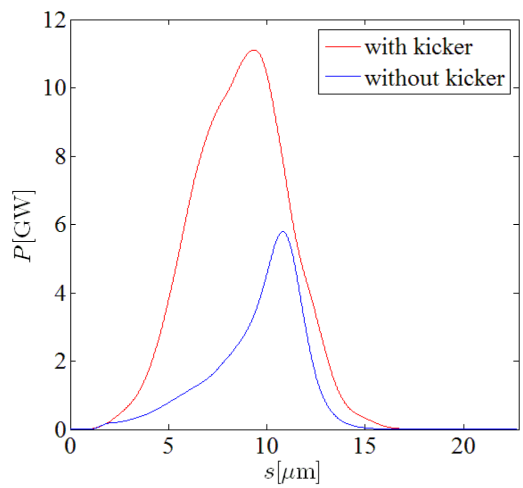

Figure 3: Temporal radiation profile of TGU with/without a kicker.

SUMMARY AND OUTLOOK

In this paper, we present the sensitivity of radiation power to the angle deflection in TGU-FEL. At the entrance of TGU, transverse angle deflection always decreases the radiation power. Since the dispersion is induced in x direction (in our case), the radiation power is more sensitive to angle deflection in this direction. Moreover, if we induce an angle deflection at a proper location together with optimized value, the TGU will perform like a linear tapered undulator (transverse-gradient preserved), which significantly improves the radiation power. Detailed study about beam transport analysis, optimization considering time-dependent effects will be presented in further studies.

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