POWER IMPROVEMENT OF FREE-ELECTRON LASER USING TRANSVERSE-GRADIENT UNDULATOR WITH EXTERNAL FOCUSING

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Abstract

Resent study shows that the transverse-gradient undulator (TGU) together with electron beams with constant dispersion can reduce the sensitivity to energy spread for FEL [1]. In this study, we numerically study FEL using TGU with external focusing. In spite of the dispersion variation, through parameter optimization, FEL using TGU with TGU achieves similar radiation to that without external focusing. To achieve a high energy exaction efficiency, the initial dispersion should be set with a shift from that corresponding to the resonant condition, and a variation of the transverse gradient in different undulator section is preferred. Other approaches, such as tapering and detuning frequency control, are also discussed to further improve the radiation power and are demonstrated with global parametric optimizations base on simulation.

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 [2]. 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) [1].

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,

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

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 [1]. Hence, we only discuss FEL using TGU in this paper.

TGU was proposed to reduce the sensitivity to the electron beam energy spread [1, 6]. By canting the magnetic poles, a linear transverse dependence of undulator field can be generated, like

$$\frac{\Delta K}{K} = \alpha x, \tag{2}$$

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

$$\eta_0 = \frac{2+K_0^2}{\alpha K_0^2}, \tag{3}$$

and keeping it constant along the TGU, the spread in electron beam's energy would be compensated.

In this paper, we studied seeded FEL using TGU with external focusing and power improvement of that. TGU with external focusing is introduced briefly. And we discuss the dispersion variation along the TGU and its effects on the FEL gain process. Possible power improvement approaches are also introduced. The energy extraction efficiency of an FEL using TGU with external focusing and different power improvement approaches are optimized separately and compared, to further understand each factor's contribution to the optimized radiation power. Simulations are done based on GENESIS, a 3D FEL simulation software, presenting reliable FEL process, proved by experiments [8].

FEL USING TGU WITH EXTERNAL FOCUSING AND POWER IMPROVEMENT

FODO cell is a kind of common external focusing structure, widely used in accelerator facilities and FEL facilities. In this study, the authors consider a simple FODO structure that focusing and defocusing quadrapoles have the same strength and are arranged alternately. The quadrapoles are arranged equidistantly with the focusing quadrapole at the TGU entrance and the layout of our

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FODO cells is illustrated on the horizontal axis in Fig. 1. The dispersion variation through the TGU with external focusing can be studied by standard accelerator matrix calculation:

$$\begin{pmatrix} \eta_f \\ \eta_f' \\ 1 \end{pmatrix} = M \begin{pmatrix} \eta_i \\ \eta_i' \\ 1 \end{pmatrix}, \qquad (4)$$

where M is the transport matrix, η_i, η_f represents for the dispersion before and after components respectively and the prime indicates $\partial/\partial z$ [9]. And at the entrance of TGU, η' is always set to 0.

Matrix calculation and GENESIS time-independent simulation are done to study the electron beam transverse size behaviour along the TGU with parameters in Table 1. And the result is shown in Fig. 1. As shown in Fig. 1, due to the effects of the strong focusing, the beam dispersion would decrease along the TGU and the simulation result agrees with matrix calculation well.

Table 1: Main Parameters

Parameter (Symbol)	Value
Beam energy (E)	500 MeV
Norm. transv. emittance ($\gamma_0\varepsilon_x$)	0.1 μm
Peak current (I_p)	5000 A
Rel.rms energy spread (σ_δ)	2%
Undulator period (λ_u)	2 cm
Undulator parameter (K)	1.93
Distance between quadrapoles (L)	2.5 m
Resonant wavelength (λ_s)	30 nm
Transverse gradient (α)	43 m^{-1}

This decreasing dispersion leads to a reduction in transverse beam size, which improves the electron beam density [10]. This promotes the FEL gain process and reduces the transverse radiation field size. However, from Eq. (3), one can find this benefit is weakened because of the mismatch between the transverse gradient and dispersion function caused by external focusing. By optimizing parameters, these two opposite effects have a balance to reach the optimal radiation power of FEL using TGU with external focusing, which is shown in the next section.

In this study, compared with the FODO cell length, the β-function period is large enough, betatron motion can be approximately described by the average β-function ($<\beta>$). For a FODO cell, under the thin-lens approximation, $<\beta>=2f$. If other parameters are fixed, the radiation power is controlled by dispersion function variation, determined by initial dispersion and average β-function. To further understand the relationship among the radiation power, initial dispersion and average β-function, grid scan over $<\beta>$ and η_i is done, shown in the below figure. As shown in figure 2, one can find that the initial dispersion should be larger than the theoretical dispersion because of the dispersion reduction along the TGU. Moreover, stronger external focusing would causes smaller final dispersion, as a result of which, the initial dispersion should be set larger to keep efficient FEL gain progress.

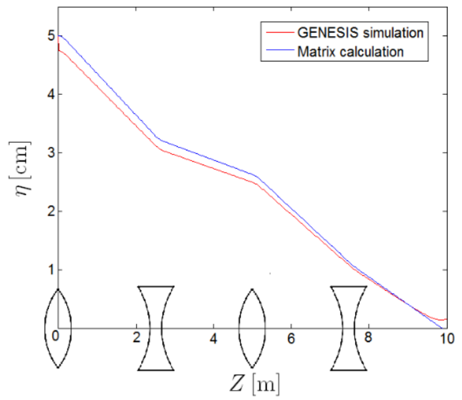

Figure 1: Electron beam transverse size variation through a 10 m-TGU with initial dispersion equal to 5 cm and focal length equal to 7 m. Traditional lens symbols are used to represent for focusing quadrupoles and defocusing quadrupoles.

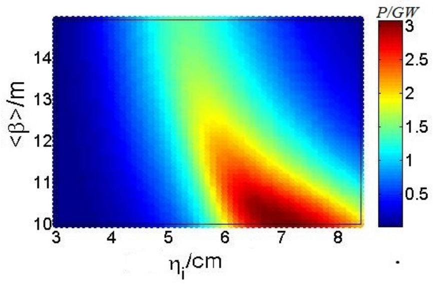

Figure 2: Contour plot of the radiation power of FEL using TGU with external focusing with respect to the initial dispersion and average β-function.

Considered the dispersion variation, the relationship between dispersion function and transverse gradient would be violated [see Eq. (3)]. To keep Eq. (3) satisfied along the TGU, the transverse gradient can be enlarged with dispersion function synchronously, which indicates that

$$\frac{2+K_0^2}{K_0^2} = \eta(Z)\alpha(Z). \qquad (5)$$

Since an undulator with a gradually increasing transverse gradient is impracticable at present, we averagely separate the undulator into two sections with different transverse gradient to roughly improve the energy-extraction efficiency.

Similar to FEL using undulator without transverse-gradient, after saturation, the radiation power oscillates around the saturation power [11]. To further extract energy from electron beam, we consider a kind of TGU with a tapered part at the end (tapered TGU with external focusing). Here and after, we use a quadratic taper profile in our numerical study, which has been proved quite efficient [12].

For an FEL using TGU without external focusing, the frequency whose power grows fastest is not that predicted by Eq. (1) but a frequency somewhat lower [13]. In analogy to this, in our case, the undulator parameter K should be set a little bit smaller to keep the FEL resonating on a frequency larger than seed laser frequency, so that the frequency whose power grows fastest would equal to the laser frequency. The effectiveness of these approaches we discuss is proved by global parametric optimization in the next section.

GLOBAL PARAMETRIC OPTIMIZATION

For physically realistic situations, we need to optimize the FEL radiation power within a finite TGU length. Considered compactness and the efficiency of power improvement, we choose to optimize the radiation power of a compact EUV-FEL generated by LPAs using a 10-meter long TGU with external focusing as radiator. To find the optimal results within a shorter time, RCDS, a both efficient and robust optimization algorithm was used in this study. Here and after, optimizations we mentioned are done using this algorithm [14].

Based on the above discussion, we did global parametric optimization of three simple models: TGU with external focusing, tapered TGU with external focusing and taper TGU with varied transverse gradient and external focusing (tapered TGU with external focusing, whose undulator is separated into two sections with different transverse gradient). Power optimization on TGU without external focusing is also done to show that external focusing doesn't lower the optimal radiation power. In addition, the optimization result considered time-dependent effects is not presented here, owing to space constraints. The parameters to be optimize and the optimized radiation power is shown in Table 2.

Table 2: Optimization of Three Simple TGU Models

Parameters	External focusing	Tapering and external focusing	Tapering ,varied transverse-gradient and external focusing
η_i	6.93 cm	6.39 cm	6.16 cm
$<\beta>$	12.94 m	12.42 m	11.21 m
K_w/K_0	0.9953	0.9980	0.9991
Z^*	-	5.84 m	5.63 m
k	-	0.085	0.102
K_w/K_0 (2nd)	-	-	0.9960
$\Delta\alpha$	-	-	37.85 T/m
ΔQ	-	-	-0.97
P_{max}	7.3 GW	28.9 GW	34.5 GW

With η_i, rms horizontal beam size, rms vertical beam size and rotation of the horizontal phase space distribution, rotation of the vertical phase space distribution and $\Delta K/K_0$ optimized, we get the optimal radiation power of FEL using TGU without external focusing is about 6.77GW. Compared with the optimal radiation power of FEL shown in the Table 2, one can find that by choosing parameters properly, the external focusing would not degrade the FEL gain. And we can find that tapering improves the radiation power of TGU with external focusing about four times and varied transverse gradient provides additional 20% power improvement. Also, if transverse gradient is increased in the second undulator section, the optimal Z* tends to be smaller and k tends to be larger, which indicates that when varied transverse gradient is considered, a more aggressive taper is preferred.

CONCLUSION

In this paper, we present numerical study result of FEL using TGU with external focusing and its possible power improvement approaches. FEL using TGU with external focusing provides radiation about that of the case without external focusing and the power improving approaches we discuss are quite effective for it. With these approaches, we finally get a fourfolds radiation power improvement. However, we only optimize the radiation power, lacking the consideration of transverse coherence. Further study focusing on optimization of both power and transverse coherence is remained to be done. And the arrangement of quadrapoles to achieve a higher energy extraction efficiency is also an interesting topic.

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