NUMERICAL INVESTIGATIONS OF TRANSVERSE GRADIENT UNDULATOR BASED NOVEL LIGHT SOURCES *

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Abstract

With the stat-of-the-art laser technique, the quality of electron beam generated from laser-plasma accelerator (LPA) is now becoming much more better. The natural merits LPA beam, e.g. high peak current, ultra-low emittance and ultra-short bunch length, etc., pave the way to the novel light sources, especially in the realm of developing much compact X-ray light sources, e.g. table-top X-ray free-electron laser, although the radiation power is limited by the rather larger energy spread than conventional LINAC. Luckily, much more power could be extracted by using the undulator with transverse gradient (TGU) when energy spread effect could be compensated. Here we introduce a novel soft x-ray light source driven by LPA based on TGU technique. Meanwhile we present a simple idea on how to achieve much higher rep-rate (e.g.∼100 kHz) storage ring based FELs boosted by TGU.

INTRODUCTION

With the adventure of the world first two hard X-ray free-electron laser — LCLS [1] and SACLA [2], scientists begins to enjoy much more exciting discoveries. However the large scale and huge investment of such kind facilities prevents XFEL from being popular worldwide, especially in the much smaller university laboratories. One of the most important aspects is the rather longer RF linear accelerator, since tens of GeV electron beam is required in the XFEL with the acceleration gradient of tens of MeV per meter.

On the other hand, the laser plasma acceleration technique could generate electron beam with energy of GeV in just centimeter scale [3], which absolutely enlightens the FEL community to build much more compact XFELs by simply replacing the large LINAC with laser plasma accelerator. While the electron beam quality from LPA could not be controlled as ideally as the conventional RF LINAC, it is reported that the LPA could provide electron beam with the energy of $\sim$ GeV [3], normalized transverse emittance of $\sim 0.1\mu\mathrm{m}$ [4], peak current of several kilo Amperes, bunch length of tens of femtoseconds or shorter, but relative energy spread of several percent level which could limit the maximum FEL output power [5].

Recently, Z. Huang et al. proposed an idea to compensate the energy spread effect in the LPA driven high-gain FELs [6], which reported that by properly transverse dispersing the LPA electron beam, the percent level energy spread in the longitudinal phase space (i.e. $\gamma - t$) could be transformed into the transversal displacement, that means by using undulators with proper transverse gradient the FEL resonant phenomenon could be maintained for electrons with different energies. The essence of TGU application in the high-gain FEL relies on the fact the sacrifice on the transverse current density increases the final extracted FEL power.

Since TGU could be used as the energy spread compensator, in the diffraction-limited storage rings, straight by pass TGU radiator line could be used to generate FELs with high rep-rate [7, 8]. Moreover, we can take the advantage of the rather larger acceptance of TGU to increase the rep-rate by slowly damping. In the following two sections two novel light sources based on TGU is presented and the numerical simulations is mainly focused.

SOFT X-RAY FEL DRIVEN BY LPA AND TGU

The theory of TGU could be simply linked by two equations, i.e.

$$a_u(x) = a_u(1+\alpha x) \tag{1}$$
$$x = \eta\frac{\Delta\gamma}{\gamma} \tag{2}$$

where a_u is the normalized undulator parameter, x is the transverse deviation, α is the transverse field gradient, η is the transverse dispersion, $\frac{\Delta\gamma}{\gamma}$ is the energy deviation. By introducing the FEL resonant equation: $\lambda_s = \lambda_u/\left(2\gamma^2\right)\left(1+a_u^2\right)$, the relationship between $\Delta\gamma/\gamma$ and $\Delta a_u/a_u$ is found as: $\frac{\Delta\gamma}{\gamma} = \frac{a_u^2}{1+a_u^2}\cdot\frac{\Delta a_u}{a_u}$. Then the compromise condition between the field gradient and transverse dispersion is worked out as,

$$\alpha\cdot\eta = \frac{1+a_u^2}{a_u^2} \tag{3}$$

Here we would like to present the numerical simulations of an LPA driven XFEL which equipped with TGU at Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences. The laser plasma accelerator is now under operation at SIOM, electron beam with nearly 1 GeV and energy spread about $\sim 3\%$, peak current of several kA is generated [9]. The next plan is to construct an soft X-ray light source driven by LPA with the name

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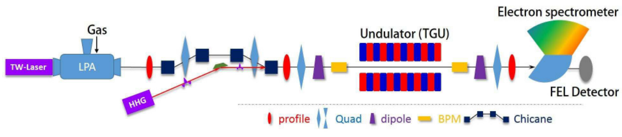

Figure 1: Schematic layout of SIOM-FEL. The layout shows five key sections, the laser plasma accelerator driven by intense Terawatt laser, the electron beam transportation line, the HHG seeding line, radiators and diagnostics for electron beam & photon.

Table 1: Main Parameters of SIOM-FEL

Parameter	Symbol	Value	Unit
Beam Energy	E_b	400	MeV
Energy Spread	σ_γ	4	MeV
Emittance	ϵ_n	0.1	mm·mrad
Beam Size	σ_x	10	μm
Peak Current	$I_{\rm pk}$	$1-2$	kA
e-Charge	Q	$\sim 10-20$	pC
Bunch length	σ_t	10	fs
Seed wavelength	$\lambda_{\rm HHG}$	30	nm
Rayleigh range of seed	Z_R	1	m
Peak power of seed	$P_{\rm seed}$	10	MW
Period of Radiator	λ_r	0.02	m
FEL wavelength	λ_s	30	nm

of SIOM-FEL, which is also an collaborated project with Shanghai Institute of Applied Physics (SINAP).

It is well known that the longitudinal coherency of FEL could be improved by seeding the electron beam with external conventional optical laser before entering into the radiator, e.g. the famous schemes HGHG [10] and EEHG [11], and the newly proposed cooled HGHG [12], etc. The next phase of SIOM-FEL will introduce the high-order harmonic (HHG) seed laser which is already in the same building of laser plasma accelerator. The HHG seed is reported can generate coherent light source around 30 nm from 800 nm optical laser. In phase-II of SIOM-FEL, TGU is also taken into account, newly designed and built TGU by SINAP will be used as the radiator to generate much more intense FEL pulses.

In this paper, numerical simulations is focusing on the SIOM-FEL seeded by HHG and boosted by TGU. Fig. 1 shows the schematic layout of SIOM-FEL. The main parameters of SIOM-FEL could be found from Table 1.

The numerical simulations are studied by the well benchmarked FEL code — GENESIS [13], which was modified for including the undulator field transverse gradient. The compromise between the transverse dispersion η and field gradient α should be found by two-dimensional optimization, as Fig. 2 shows, it is clearly that the optimal FEL output power decreases from 1.6 GW to only 0.4 GW for the case of 1% and 2% energy spread, respectively.

To envision the promising future, here we fix the energy spread to be 1%, and apply the optimal $(\alpha, \eta) = (164\,\mathrm{m}^{-1}, 1.32\,\mathrm{cm})$, which means tilt angle of $\sim 21°$ for

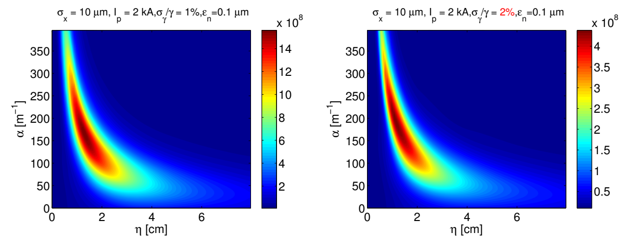

Figure 2: Two-dimensional optimization of α and η with the electron parameters of $\sigma_x = 10\,\mu\mathrm{m}$, $I_{\rm pk} = 2\,\mathrm{kA}$, $\epsilon_n = 0.1\,\mu\mathrm{m}$, the relative energy spread used here is 1% (*left*) and 2% (*right*) respectively.

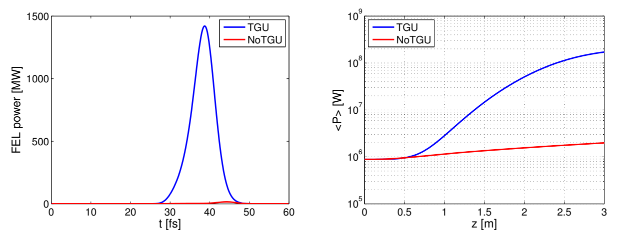

Figure 3: Simulated FEL pulse profile (*left*) and gain curve (*right*) with the case of TGU and normal undulator, electron parameters used here are $\sigma_x = 10\,\mu\mathrm{m}$, $I_{\rm pk} = 2\,\mathrm{kA}$, $\epsilon_n = 0.1\,\mu\mathrm{m}$, $\sigma_\gamma/\gamma = 1\%$.

Halbach permanent undulator [14] is required, however the numerical simulation shows that with the much more practical tilt angle of $\sim 7°$ ($\alpha = 50\,\mathrm{m}^{-1}$) the radiation power still could be up be $\sim 200\,\mathrm{MW}$.

The time-dependent simulations are also preformed for the case with TGU and normal undulator, respectively, both are seeded by HHG source. Fig. 3 shows that after 150 periods radiator, the HHG seed is amplified over 140 times by TGU while almost only 2 times by normal undulator, evident exponential growth could be seen.

It is noted that even if the electron beam from LPA with worse quality, e.g. $\sigma_x = 50\,\mu\mathrm{m}$, $\epsilon_n = 1.0\,\mu\mathrm{m}$, TGU still could amplified the seed by 10 times.

HIGH REP-RATE XFEL DRIVEN BY USR AND TGU

The Beijing Advanced Photon Source (BAPS) is a major facility being planned for a new research center in northeast Beijing by Chinese Academy of Sciences. The schematic layout of BAPS could be found from Fig. 4, one can see two large rings with the circumference of about 1.2 km, the different vertical latitude allows for the light beam extraction from both inner and outer rings [15]. Here we consider the FEL option for BAPS, which emittance could be lower down to diffraction-limited, by using TGU in the bypass straight line, the energy spread effect could be compensated thus to achieve much higher FEL power output.

Below shows the main parameters when running under the high rep-rate FEL mode, in which TGU is used as the main straight radiator lines, with the aim to get ≥ 100 kHz

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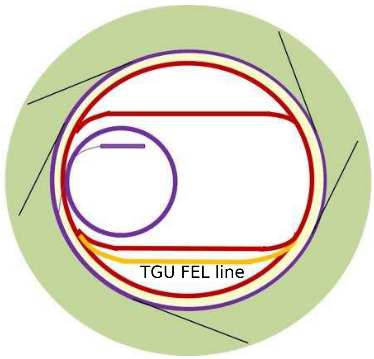

Figure 4: Schematic layout of BAPS, with the beam energy of 5 GeV, the yellow bypass straight line (total length could be up to $100 - 200\,\mathrm{m}$) is designed for generating FELs.

Table 2: Parameters of BAPS-FEL.

Parameter	Symbol	Value	Unit
Beam Energy	E_b	3.0	GeV
Energy Spread	σ_γ/γ	0.1%	
Peak Current	I_p	$100 - 300$	A
Undulator Period	λ_u	0.03	m
Undulator Parameter	K_0	1.61	
Undulator Length	L_u	180	m
Average beta x	$\bar{\beta}_x$	70	m
Average beta y	$\bar{\beta}_y$	20	m
Transverse Dispersion	η	4.5	cm
Transverse Gradient	α	40	m^{-1}
FEL wavelength	λ_s	1.0	nm
FEL peak power	P_{pk}	~ 200	MW
FEL pulse energy	W_{FEL}	~ 200	μJ
FEL flux	F_{FEL}	1×10^{12}	#/pulse

rep-rate by slowly damping.

We introduce the coupling factor of 1% into the electron beam, and the normalized emittance used here is $\epsilon_x = 0.6\,\mu\mathrm{m}$, $\epsilon_y = 0.006\,\mu\mathrm{m}$. On entering the straight bypass line, the electron beam is first vertically dispersed to form round shape transverse beam size, then the FEL amplified along TGU. The optimization of transverse gradient and transverse dispersion could be found from Fig. 5. The FEL power gain curve could be found under different peak currents from Fig. 6, also shows the cases with normal undulators.

One of the greatest advantages of storage rings based FELs is the high repetition rate, which mean higher average brilliance. However the FEL process in the bypass straight line will absolutely destroy the electron beam quality equilibrium, extra time is required to restore such equilibrium state, the damping time is usually of msec order, which means the rep-rate should drop from MHz to kHz level. Here we propose that the rep-rate could be increased by let the electron beam passes through the TGU line several times before damping, or slowly damping, since TGU is an energy spread compensator, the FEL power should almost be of the same order level within the round trip passing TGU (see Fig. 7). The consequence is that the rep-rate could be increased by 1-2 orders, i.e. the goal of BAPS-FEL to 10-100 kHz rep-rate.

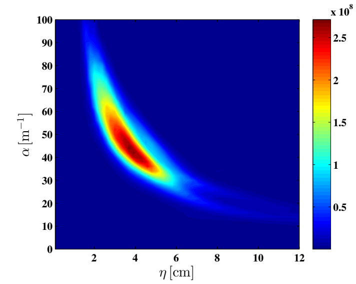

Figure 5: Optimization between the transverse gradient and dispersion for BAPS-FEL.

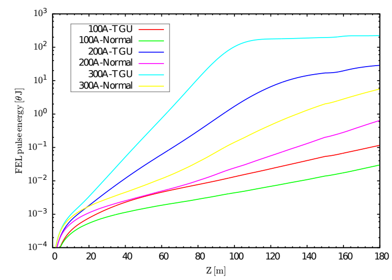

Figure 6: Time-dependent simulated FEL power gain curve with different peak currents.

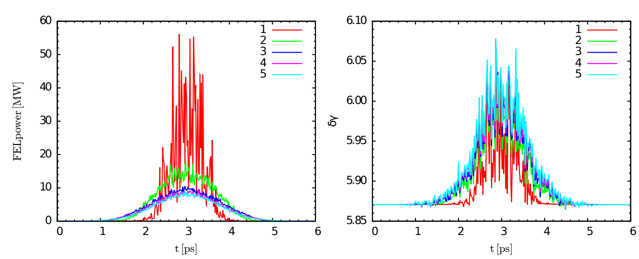

Figure 7: Time-dependent simulated FEL power and energy spread within 5 trips along TGU by pass line (no damping).

CONCLUSIONS

In this paper, the application of transverse gradient undulator in the free-electron laser has been carefully investigated by numerical simulation approach. The much more compact X-ray free-electron laser — SIOM-FEL could has the ability to generate several hundred MW FEL power if TGU is properly used. The high repetition rate storage ring based FEL could also been working in the high-gain regime, even higher rep-rate could be achieved if let the electron beam slowly damp in the bypass TGU line and storage rings. The preliminary numerical simulations of BAPS-FEL indicate that the rep-rate of BAPS-FEL could be up to no less than 50 kHz, 100 kHz is still the goal to achieve. Finally it should be optimistic that beam quality of LPA especially the energy spread once drops down to

0.1% region, the table-top XFEL driven by LPA will open up new realms.

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