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SUPPRESSION OF MICROBUNCHING INSTABILITY VIA A TRANSVERSE GRADIENT UNDULATOR

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Abstract

The microbunching instability in the linear accelerator (linac) of a free-electron laser facility has always been a problem that degrades the electron beam quality. In this paper, a quite simple and inexpensive technique is proposed to smooth the electron beam current profile to suppress the instability. By directly adding a short undulator with transverse gradient field right after the injector to couple the transverse spread into the longitudinal direction, additional density mixing in the electron beam is introduced to smooth the current profile, which results in the reduction of the gain of the microbunching instability. The magnitude of the density mixing can be easily controlled by turning the strength of the undulator magnet field. Theoretical analysis and numerical simulations demonstrate the capability of the proposed technique in the accelerator of an X-Ray free-electron laser.

INTRODUCTION

X-Ray free-electron lasers (FELs) are being developed to serve as ultra-short, tuneable, intensity radiation sources for advanced user applications. In the recent years, the successful user operation of the first FEL facilities in soft and hard x-Ray regimes announced the birth of the x-Ray laser. High intensity electron beams of sub-picosecond (sub-ps) length typically required for x-Ray FELs are usually obtained by compressing longer beams in magnetic bunch compressors at relativistic energies. The bunch compressor manipulates longitudinal phase space of the electron beam with a considerable energy chirp by introducing the dependence of particle's longitudinal position on their relative energy. The bunch length therefore can be significantly compressed by the compressor. However, in the compression process, the initial small energy and density perturbation in the electron bunch can be amplified with a large gain factor in many cases, which will increase the fragmentation of the longitudinal phase space and dilute the emittance. This process of amplification is usually known as the microbunching instability, and it will seriously degrade the FEL performance thereafter.

The microbunching instability can be suppressed by various techniques that rely on the electron beam manipulation. The idea of using a transverse gradient undulator (TGU) to mitigate the effects of electron beam energy spread in FEL oscillators has been initially described in reference [1]. Recently, this idea has been applied to laser-plasma accelerator driven high-gain FELs. It is found later that TGU is a functional device that provides an additional measure for manipulating the electron beam via transverse-to-longitudinal phase space coupling. One of the applications of this manipulation technique is to perform the phase merging effect for significantly improving the frequency up-conversion efficiency of a seeded FEL. In this paper, a quite simple and inexpensive technique based on the transverse-to-longitudinal phase space coupling is proposed and studied for suppression the microbunching instability of the electron beam. It is found that by directly adding a TGU after the injector in a linac, the gain of the microbunching instability in the electron beam can be effectively suppressed. Compared with the previous techniques, this method is quite simple and could be easily applied on all existing FEL facilities in addition to the laser heater. Moreover, the change of the chromaticity introduced by the scheme in this paper is ignorable and the transverse emittance of the beam is preserved well enough throughout the whole linac lattice after transverse matching, which is considered as another great advantage.

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METHODS

The schematic layouts of the proposed technique are shown in Figure 1. In Figure 1(a), a short TGU is added after accelerating section L1 and another one is added after L2 in the linac, the linear energy chirp of the beam exists in both the locations. In Figure 1(b), one TGU is placed right after the injector where there is no energy chirp. The selections of the locations of TGUs will be discussed later on in this paper.

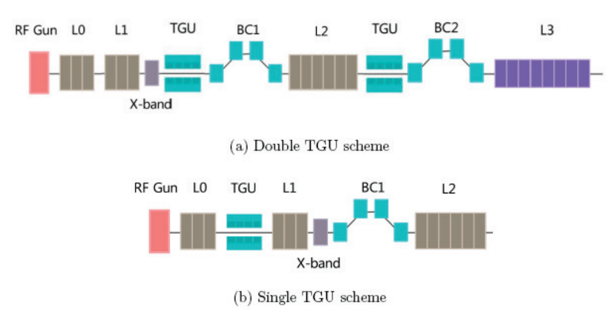

Figure 1: (Color) Layouts of two TGU schemes.

TGU, like what described by its own name, is an undulator with transverse gradient between magnetic poles. Such a device can be realized by canting the poles of an regular undulator and the gradient is usually made in the horizontal direction. Because electrons at different horizontal positions feel different magnetic fields, the path length of an electron traversing TGU depends on its transverse coordinate at the entrance of TGU. Because of

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that, the first-order transport matrix of TGU in ***(x, x', y, y', s***, E) phase space can be derived (ignore the vertical effects)

$$\mathbf{X} = \begin{bmatrix} 1 & L_T & 0 & 0 & 0 & \tau L_T/2 \\ 0 & 1 & 0 & 0 & 0 & -\tau \\ 0 & 0 & 1 & L_T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \tau & \tau L_T/2 & 0 & 0 & 1 & -\tau^2 L_T/6 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

where L_T is the effective length of TGU and τ is the strength of TGU. In the TGU transport matrix (1), one can see that the effective elements R_{51} and R_{26} are of the same value but in opposite signs.

To investigate the behavior of the microbunching instability, the density perturbation in one wavelength is divided into multiple slices. Because the wavelength of the microbunching instability is usually much smaller than the bunch length, the assumption of the uniform longitudinal density distribution within a beam slice is employed in the following discussion. If a linear energy chirp is added on the electron beam with Gaussian energy distribution before the first TGU (TGU 1), the longitudinal phase space distribution of the beam particles within a thin slice reads

$$f_0(z, \delta_\gamma) = \frac{I_0}{\sqrt{2\pi}\sigma_\gamma} \exp\left[-\frac{(\delta_\gamma - h\gamma_0 z)^2}{2\sigma_\gamma^2}\right]. \qquad (2)$$

Here we define z the longitudinal coordinate of a beam particle within the bunch, where z=0 represents the beam center, and z>0 is behind the beam center. I_0 is the longitudinal beam current, γ_0 is the relativistic central beam energy, σ_r is the initial uncorrelated energy spread, $\delta_\gamma = \Delta\gamma(\gamma_0)^{-1}$ is the energy divergence of a particle, $h = d\delta(\gamma dz)^{-1}$ is used for quantifying the beam energy chirp. After passing through the first short TGU with period length λ_u, period number N_u, transverse gradient α and central undulator parameter K_0, electrons at different horizontal positions x will see different K values, where $K(x) = K_0(1 + \alpha x)$, which results in different path lengths and converts the longitudinal coordinate into

$$z' \approx z + \frac{L_m K_0^2 \alpha}{2\gamma^2} x, \qquad (3)$$

where γ represents the energy of the particle and $L_m = N_u \lambda_u$ is the length of TGU. Defining $\tau = L_m K_0^2 \alpha (2\gamma^2)^{-1}$ the gradient parameter of GU for particle energy γ , one can easily see that τ is essentially the R_{51} element in the transport matrix of TGU. Note that the contribution from x' is ignored as explained in the following discussions.

Without losing generality, assuming Gaussian distribution in the horizontal, after passing through TGU, the distribution of the beam particles within a longitudinal thin slices becomes

$$f_0(z, x, \delta_\gamma) = \frac{I_0}{2\pi\sigma_\gamma\sigma_x} \exp\left[-\frac{(\delta_\gamma - h\gamma_0 z - h\tau\gamma_0 x)^2}{2\sigma_\gamma^2}\right] \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \qquad (4)$$

where x is the horizontal position of a beam particle and x=0 is in the center of the beam. For a sufficiently thin beam slice, we make the assumption that all the particles within the slice have the same longitudinal coordinate z. It is found in equation (4) that the horizontally correlated energy spread is converted into longitudinally uncorrelated energy spread with the energy chirp $h\tau$, which increases the slice energy spread of the beam before compression. As a result, the gain of the microbunching instability during compression is reduced. After the integration along the horizontal axis, we obtain the energy distribution at z without horizontal dependency

$$f_0(z, \delta_\gamma) = \frac{I_0}{\sqrt{2\pi}\sigma'_\gamma} \exp\left[-\frac{(\delta_\gamma - h\gamma_0 z)^2}{2\sigma'^2_\gamma}\right] \qquad (5)$$

where $\sigma'_\gamma = \sqrt{\sigma_\gamma^2 + (h\tau\gamma_0\sigma_x)^2}$, which can be much larger than the original slice energy spread σ_γ.

Another important capability of TGU is to introduce the longitudinal mixing from the transverse spread. Following the same method in reference [2, 3, 4], based on equation (5) and including the contribution from the horizontal beam distribution, the final gain of the microbunching instability after the passage through the bunch compressor with TGU taken into account reads

$$G_f \approx G_0 \exp\left(-\frac{k^2 R_{56}^2 \sigma'^2_\gamma}{2}\right) \exp\left(-\frac{k^2 \tau^2 \sigma_x^2}{2}\right) \qquad (6)$$

In equation (6), the two terms on the right gives the damping introduced by the energy spread and the longitudinal mixing, respectively. And one can see that the gain of the microbunching instability is suppressed by two factors: one is the extra uncorrelated energy spread introduced by TGU when the beam energy chirp exists, another is the decrease of the bunching factor due to the horizontal-longitudinal coupling throughout TGU.

Based on the discussions above, we propose a scheme (scheme 1) of suppressing the microbunching instability via TGU. In this scheme, a short TGU (TGU 1) is placed right before the first bunch compressor (BC1) where the beam is chirped in the longitudinal phase space to introduce the extra uncorrelated beam energy spread (Figure 1(a)). And because the achromaticity introduced by TGU 1 (R_{26} = -R_{51}) is large enough to introduce noticeable horizontal emittance growth thereafter, we need another TGU (TGU 2) at the end of L2 to recover the emittance, which is somehow complicated.

Compared to scheme 1, the one based on the horizontal-longitudinal coupling is relatively simple and easier to implement (scheme 2). Moreover, because it does not require TGU to be placed at where the energy chirp is large, the extra emittance growth introduced by TGU will be small. Therefore in the rest part of this paper we carry out our discussion based on scheme 2. In scheme

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2 a short TGU is placed at the exit of the injector where there is no energy chirp, as what is shown in Figure 1(b). And the microbunching instability is suppressed by the longitudinal-transverse coupling introduced by the TGU only. In the following section, we present a proof of principle of this scheme and one can clearly see the significant decrease of the energy and current modulations at the end of the linac with TGU implemented in the lattice.

SIMULATION STUDIES

We perform our analysis based on the machine model in Figure 1(b) to show the principle and possible performance of the proposed technique. For the aim of simplicity, the second bunch compressor (BC2) and the third linac section (L3) are not included in the model. Note that in this case the small beam energy spread ($<10^{-4}$) is required in order to avoid the transport matrix element R_{26}-introduced emittance growth. We took the nominal parameters of the Shanghai X-ray FEL facility (SXFEL) in the simulations, which are shown in Table 1. Moreover, since the length scale in which the structural impedance is effective is much longer than that of microbunching wavelength, we may neglect the effects from the linac wakefields in the following discussions without compromising accuracy.

Table 1: Main Beam and Linac Parameters in the Study

Parameter	**Value**
Bunch charge (nC)	0.5
Beam energy out of injector (MeV)	130
Bunch length (FWHM, ps)	10
Peak current before compression (A)	50
Compression ratio of BC	4

The simulation starts right after L0 and ends before L2. To illustrate the problem, two typical cases are analyzed: one is the beam with the density (current) modulation of $\lambda = 50\mu m$ in wavelength and 10% in amplitude but no modulation of energy, another is the one with the energy modulation of $\lambda = 50\mu m$ in in wavelength and 1% in amplitude but no modulation of current. The particle tracking code ELEGANT [5] is used to do the simulation in linac and a 3-D algorithm based on the fundamentals of electrodynamics is employed to do the simulation in TGU. The simulation starts at the exit of the injector where the beam energy is about 130 MeV, and the peak current is about 60 A. As mentioned above, a variable-gap TGU with 12 periods of 80 mm period length, $B_0 \approx 1.07\,T$ and transverse gradient $\alpha = 100m^{-1}$ is adopted right after the injector in the simulation. After passage through TGU and the chirp section (L1), the electron beam is compressed and then accelerated to ~420 MeV at the end of the linac. The horizontal and the vertical beam size $\sigma_{x,y} \sim 0.56\,mm$ at the entrance of TGU, and 10 million macro-particles with total charge of 0.5 nC are used in the simulation. To save the computing time, we output the beam information right after the bunch compressor (BC) instead of the end of the linac, which makes no difference because the microbunching information at this location is adequate to demonstrate the problem, and the correlated energy chirp at this location plays no role in our discussion. Figure 2 shows the comparison between the longitudinal current profiles after BC with and without TGU inserted in the lattice. In both the cases, we can clearly see in the figure that the micro-bunches are reduced significantly because of TGU.

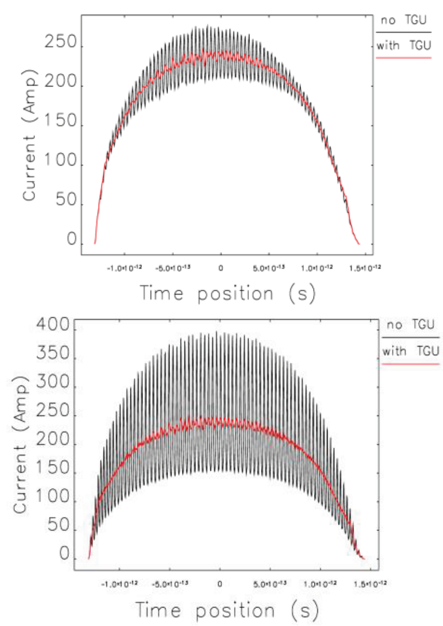

Figure 2: (Color) Longitudinal beam current profiles with (red) and without (blue) TGU at BC exit. Top: with initial current modulation; bottom: with initial energy modulation.

CONCLUSION

The theoretical analysis shows that TGU was able to suppress the instability by two factors: additional slice energy spread and horizontal-longitudinal coupling. Due to the simplicity of the longitudinal-transverse mixing, we employed this method to demonstrate the feasibility and the efficiency of the TGU scheme with the typical parameters of a mid-energy electron linac. As the result, the significant suppression of the instability comparing to the one without TGU in the lattice were observed in the simulation. Because the TGU scheme owns the advantages such as good efficiency, less complexity and better transverse matching, it opens a new way for us to improve the performance of the X-Ray free-electron laser, and can be a good device to control the microbunching instability in addition to a laser heater. Finally, like what we have described in this article, TGU is also able to increase the uncorrelated energy spread of the beam so as to suppress the microbunching instability. This will be the next topic of us to study in detail.

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