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 a 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 varying the strength of the undulator magnetic field. Theoretical analysis and numerical simulations demonstrate the capability of the proposed technique in the accelerator of an x-ray free-electron laser.

1. Introduction
X-ray free-electron lasers (FELs) are being developed to serve as ultra-short, tunable, intensity radiation sources for advanced user applications. In recent years, the successful user operation of the first FEL facilities [1–4] 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 the longitudinal phase space of the electron beam with a considerable energy chirp by introducing the dependence of a particle’s longitudinal position on its relative energy. The bunch length therefore can be significantly compressed. 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 [5, 8, 9]. 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 through various techniques that rely on electron beam manipulation [7, 10–13]. The most popular technique used in many facilities is a laser heater, which employs a polarized laser pulse in a short undulator located in the middle of a chicane to increase the uncorrelated energy spread of the electron beam [10]. The need for a laser heater comes from the fact that the electron beam emitted from a high brilliance photo-cathode gun usually has an extremely small uncorrelated local energy spread which is on the order of a few keV [14, 15]. The extra uncorrelated energy spread introduced by the laser heater provides Landau damping to an extent that reduces the gain of the instability and therefore the microbunching instability is suppressed. The laser heater system at the Linac Coherent Light Source (LCLS) was successfully commissioned and started to operate in 2009 [16]. By adjusting the power of the laser pulse, the laser-induced uncorrelated energy spread could be controlled to optimize the FEL working point. Recently, alternative techniques [7, 11–13] have also been proposed for suppressing the microbunching instability via other methods of electron beam manipulation, such as the scheme of deflecting cavity [13], and bending magnets [7], etc. However, most of the methods are complex and not as easy to apply to the existing FEL facilities.
The idea of using a transverse gradient undulator (TGU) to mitigate the effects of electron beam energy spread in FEL oscillators was initially described in [17]. Recently, this idea has been applied to laser-plasma accelerator driven high-gain FELs [16]. Later, it was found that the 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 [18, 19]. In this paper, a quite simple and inexpensive technique based on the transverse-to-longitudinal phase space coupling is proposed and studied for the suppression of 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 to previous techniques, this method is quite simple and could be easily applied to all existing FEL facilities in addition to the laser heater. Moreover, the change of the chromaticity introduced by the scheme in this paper is negligible 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.

In section 2, the methods to suppress the microbunching instability by the TGU are analyzed theoretically and equations are derived to illustrate the idea. In section 3, a simulation is carried out to demonstrate the idea and the issues that may appear in a real machine are analyzed in detail. Concluding remarks are made in section 4.

2. 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 locations. In figure 1(b), one TGU is placed right after the injector where there is no energy chirp. The selection of the locations of the TGUs will be discussed later on in this section.

The TGU, as its name suggests, is an undulator with a transverse gradient between magnetic poles. Such a device can be realized by canting the poles of a 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 a TGU depends on its transverse coordinate at the entrance of the TGU. As a result, the first-order transport matrix of the TGU in $(\vec{x}, x', \vec{y}, y', \vec{z}, E)$ phase space can be derived (ignoring vertical effects)

$$
X = \begin{pmatrix}
1 & L_T & 0 & 0 & 0 & \tau L_T/2 \\
0 & 1 & 0 & 0 & 0 & -\tau \\
0 & 0 & 1 & L_T & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
\tau & \tau L_T/2 & 0 & 0 & 1 & -\tau^2 L_T/6 \\
0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix},
$$

Figure 1. Layouts of two TGU schemes.
where $L_T$ is the effective length of the TGU and $\tau$ is its strength. In the TGU transport matrix (1), one can see that the effective elements $R_{53}$ and $R_{26}$ are of the same value but with opposite signs. The elements will be discussed in detail in the following paragraphs.

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 TGU, the longitudinal phase space distribution of the beam particles within a thin slice reads [5]

$$f_{0}(z, \delta_{\gamma}) = \frac{I_0}{\sqrt{2\pi} \sigma_{\gamma}} \exp \left[ -\frac{(\delta_{\gamma} - h\gamma_0 z)^2}{2\sigma_{\gamma}^2} \right].$$

(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, $\gamma_0$ is the relativistic central beam energy, $\sigma_{\gamma}$ is the initial uncorrelated energy spread, $\delta_{\gamma} = \delta\gamma(x_{\delta})^{-1}$ is the energy deviation of a particle, $h = d\delta(\gamma dz)^{-1}$ is used for quantifying the beam energy chirp. After passing through the short TGU with period length $\lambda_{nu}$, period number $N_{nu}$, transverse gradient $\alpha$ and central undulator parameter $K_0$, electrons with different horizontal positions $x$ will see different $K$ values, where $K(x) = K_0(1 + \alpha x)$ [17]. Based on the TGU matrix (1), it results in different path lengths and converts the longitudinal coordinate into

$$z_f = z + \tau x + \frac{\tau L_T}{2} = \frac{\tau^2 L_T}{6} \delta_{\gamma},$$

(3)

where $\gamma$ represents the energy of the particle, $L_T = N_{nu} \lambda_{nu}$ represents the length of TGU and $\tau = L_T K_0^2 \alpha (2\gamma^2)^{-1}$ is the gradient parameter of TGU for particle energy $\gamma$.

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

$$f_{0}(z, x, \delta_{\gamma}) = \frac{I_0}{(2\pi)^{3/2} \sigma_{\gamma} \sigma_{x}} \exp \left( -\frac{x^2}{2\sigma_{x}^2} \right) \exp \left( -\frac{x^2}{2\sigma_{z}^2} \right) \times \exp \left[ -\frac{(\delta_{\gamma} - h\gamma_0 z - h\gamma_0 \tau x - h\gamma_0 \tau L_T x'/2 + h\gamma_0 \tau^2 L_T \delta_{\gamma}/6)^2}{2\sigma_{\gamma}^2} \right] \approx \frac{I_0}{(2\pi)^{3/2} \sigma_{\gamma} \sigma_{x}} \exp \left( -\frac{x^2}{2\sigma_{x}^2} \right) \times \exp \left[ -\frac{(\delta_{\gamma} - h\gamma_0 z - h\gamma_0 \tau x)^2}{2\sigma_{\gamma}^2} \right].$$

(4)

where $x$ is the horizontal position of a beam particle and $x = 0$ is in the center of the beam. In the last step, we ignored the last two terms in the third exponential function because in a TGU the absolute value of the beam divergence angle $x'$ is much smaller than that of $x$, and the TGU gradient parameter $\tau$ is also a very small number. 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 a 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. Without losing generality, we look at the central part of the beam where the slice energy spread is almost the same. To obtain the rms energy spread in the middle slice where $z = 0$, for a given horizontal beam size $\sigma_{x}$, we first perform the integral along the horizontal axis and obtain the energy distribution without horizontal dependency.

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where \( \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^2} dt \) is the error function. Equation (5) shows us a typical Gaussian distribution function with the rms energy spread

\[
\sigma' = \sqrt{\sigma_z^2 + (h \tau_{0} \sigma_x)^2},
\]

and it can be much larger than the original slice energy spread \( \sigma_z \). Therefore, the energy distribution of the beam at slice \( z \) becomes

\[
f_0(z, \delta_r) = \frac{I_0}{\sqrt{2\pi \sigma_r'}} \exp \left[ -\frac{(\delta_r - h \gamma z)^2}{2 \sigma_r'^2} \right].
\]

Another important capability of the TGU is to introduce longitudinal mixing from the transverse spread. We follow similar methods to \([5\text{--7}]\), and make use of the current distribution function in \([5]\), which is

\[
I(s) = \frac{I_0}{\sqrt{2\pi \sigma_r'}} \int_{-\infty}^{\infty} d\delta_r \exp \left( -\frac{(\delta_r - h \gamma z)^2}{2 \sigma_r'^2} \right),
\]

where \( R_{56} \) is the momentum compaction of the bunch compressor, \( k = k_0(1 + h R_{56}) \) is the modulation wave number after compression, with \( k_0 \) the modulation wave number before compression and \( h \) the energy chirp. \( \Delta \gamma \) represents the energy modulation amplitude defined in \([5]\) and \( \sigma_r' \) is the equivalent energy spread defined in equation (6). By substituting \( z \) in equation (3) into (8) as \( z \), in such a way as to take into account the TGU effects, and following the same procedure as in \([5]\), we obtain the final gain of the microbunching instability after the passage through the bunch compressor with the TGU taking effect

\[
G_{f} = G_{0} \exp \left( -\frac{k^2 R_{56}^2 \sigma_r'^2}{2} \right) \exp \left( -\frac{k^2 \tau' \sigma_r'^2}{2} \right) \exp \left( -\frac{k^2 \tau' \sigma_r'^2}{8} \right) \exp \left( -\frac{k^2 \tau' \sigma_r'^2}{72} \right) \approx G_{0} \exp \left( -\frac{k^2 R_{56}^2 \sigma_r'^2}{2} \right) \exp \left( -\frac{k^2 \tau' \sigma_r'^2}{2} \right),
\]

where \( G_{0} = k |R_{56}| I_{0} Z(k) (\gamma_{0} I_{0} Z_{0})^{-1} \), with \( Z_{0} = 377 \Omega \) the free-space impedance and \( Z(k) \) the longitudinal impedance of wave number \( k \). Note the last two terms are dropped because the values of the independent variables inside the exponential functions are too small compared with the first two.

In equation (9), the two terms on the right give the damping introduced by the energy spread and the longitudinal mixing. In the equation, we can see that the gain of the microbunching instability is suppressed by two factors: one is the extra uncorrelated energy spread introduced by the TGU when the beam energy chirp exists, another is the decrease of the bunching factor due to the horizontal–longitudinal coupling throughout the TGU.
Based on the discussions so far, two schemes of suppressing the microbunching instability via a TGU can be proposed. In the first scheme (scheme 1, see figure 1(a)), 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. The achromaticity introduced by TGU 1 \((R_{3y} = -R_{3x})\) is large enough to introduce noticeable horizontal emittance growth thereafter, therefore we need another TGU (TGU 2) at the end of L2 to recover the emittance, which is somewhat complicated.

Compared with scheme 1, the one based on the horizontal–longitudinal coupling is relatively simple and easier to implement (scheme 2, see figure 1(b)). In this scheme a short TGU is placed at the exit of the injector where there is no energy chirp, and the microbunching instability is suppressed by the longitudinal–transverse coupling introduced by the TGU only. Moreover, because it does not require the TGU to be placed at where the energy chirp is large, the extra emittance growth introduced by the TGU will be considerably small. Therefore, as a simpler demonstration, in the rest of this paper we only carry out our discussion based on scheme 2. In the following section, we present a proof of principle of this scheme and one can clearly see a significant decrease in the energy and current modulations at the end of the linac with the TGU implemented in the lattice.

### 3. 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 simplicity, the second bunch compressor (BC2) and the third linac section (L3) are not included in the model. In the model, one X-band structure is employed to suppress the second-order nonlinear components in the longitudinal phase space to avoid the undesired growth of transverse emittance and slice energy spread. To simplify the problem, only one magnetic chicane-type BC is used to compress the beam to arrive at the required peak current, and another section of accelerating tubes (L2) is included after the BC to compensate the energy chirp introduced by L1. Note that in this case the small beam energy spread \((< 10^{-5})\) is required in order to avoid the transport matrix element \(R_{25}\)-introduced emittance growth, and we will discuss it in detail at the end of this section. 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 \([22, 23]\), we may neglect the effects from the linac wakefields in the following discussions without compromising accuracy.

The simulation starts right after L0 and ends before L2. To illustrate the problem, two typical cases are analyzed: one has the beam with the density (current) modulation of \(\lambda = 50 \mu m\) in wavelength and 10% in amplitude but no modulation of energy, another has the energy modulation of \(\lambda = 50 \mu m\) in wavelength and 1% in amplitude but no modulation of current. The particle tracking code ELEGANT \([21]\) is used to do the simulation in linac and a 3D algorithm based on the fundamentals of electrodynamics \([27]\) is employed to do the simulation in the 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 \(\alpha = 100 m^{-1}\) is adopted right after the injector in the simulation. After passage through the TGU and the chirp section (L1), the electron beam is compressed at a ratio of 4, and then accelerated to ~420 MeV at the end of the linac. The horizontal and the vertical beam size \(\sigma_x \sim 0.56 mm\), and \(\sigma_y \sim 0.58 mm\) at the entrance of the TGU, and 10 million macro-particles with total charge of 0.5 nC are used in the simulation. Figure 2 shows the initial current profile in case 1 and the initial distribution of the slice energy spread dy in case 2.

In both cases, because there is no energy chirp of the beam in the TGU, the beam slice energy spread does not increase, which means only the second term due to the longitudinal–transverse mixing in equation (9) takes effect. In the first case, the mixing smears out the density (current) modulation and in the second case, it

| Parameter                          | Value         |
|-----------------------------------|---------------|
| bunch charge (nC)                 | 0.5           |
| beam energy out of injector (MeV) | 130           |
| bunch length (FWHM) at exit (ps)  | 10            |
| peak current before BC (A)        | 50            |
| linac length up to BC (m)         | 17.3          |
| \(R_{3y}\) of BC (mm)             | -48           |
| beam energy after L2 (MeV)        | 422.0         |
| compression ratio of BC (m)       | ~5            |

Table 1. Main beam and linac parameters \([20]\) used in our study.
diminishes the beam energy modulation. Both result in a great reduction of the initial modulations, which will be shown in the following.

To save computing time, we output the beam information right after the 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 3 shows the comparison between the longitudinal current profiles after the BC with and without the TGU inserted in the lattice. In both cases, we can clearly see in the figure that the micro-bunches are reduced significantly because of the TGU.

Nowadays, the laser heater is recognized as a common method to control the microbunching instability in the linac of an FEL facility by increasing the uncorrelated beam energy spread through the laser-beam interaction. However, in order to totally smear out the final energy modulation, the power of the laser heater must be large enough and, as a result, the final slice energy spread may not meet the requirement of a seeded FEL. As a comparison, because of the intrinsic mechanism of the TGU method discussed in this paper, we do not have to increase the local energy spread by random heating, therefore the relatively smaller final slice energy spread can be achieved in the TGU scheme. To illustrate the problem, figure 4 shows the longitudinal beam phase spaces at the exit of the BC when the initial beam density or energy modulation are included, with and without the TGU in the lattice, and the ones with and without the laser heater with the initial density modulation added into the beam. In all the plots, the energy chirp (or the correlated energy spread) is removed from the phase space. For the laser heater, in order to fully smear out the energy modulation at the end of the linac, the laser wavelength is 800 nm with a peak power of 0.54 MW and the undulator period is 5 cm with 0.5 m total length. In figure 4(f), one can clearly see the relative larger slice energy spread around the core for a laser heater to achieve the same goal.
At the end of this section, a few issues need to be noted. One is the $R_{26}$-introduced emittance growth. As we can see in the TGU transport matrix (1), when the $R_{51}$ element takes effect, so does the $R_{26}$. Since the $R_{26}$ element corresponds to the coupling between the longitudinal energy spread and the horizontal beam emittance, a non-trivial energy spread could introduce a noticeable horizontal emittance growth. To avoid that, one needs a very small energy spread right before the TGU, i.e., $< 10^{-4}$. In this case the transverse emittance can be preserved very well during the beam transportation through $\beta$-matching before and after the TGU by tweaking the quadrupoles in the vicinity. In our simulation, the emittance growth is less than 9% at the exit of the BC. In our discussion, in order to demonstrate the problem, an ideal beam with nearly flat time–energy correlation was adopted; in the real machine however, it could be obtained via the back-tracking method proposed by Cornacchia and Penco et al in theory [24, 25] and experimentally demonstrated by Penco et al [26]. This method is able to reduce the longitudinal beam phase space curvature introduced by the structural wakefields and those provided by the RF accelerating sections and BCs simultaneously at a certain point in a linac, which is not so convenient since the signs of those curvatures are not usually the same. The only requirement of this method is the proper choice of the initial current profile out of the cathode, which can also

![Figure 4. Longitudinal phase space of the electron beam at the exit of the BC with energy chirp removed.](image-url)
be obtained by modern laser shaping techniques [26]. On the other hand, in the real FEL case, because only a small fraction of the beam (<20% of the total length for SXFEL) is needed for lasing, one can even obtain the beam of the required small energy spread through the regular way, i.e. implementing a high–harmonic RF cavity or a corrugated structure [28] and then cut out a small fraction of the ‘long’ beam to meet the condition. Therefore, in this paper it is valid to make the flat longitudinal beam phase space assumption for the proof of principle.

Another issue that needs to be mentioned is the jitter problem. The matrix element $R_{2x}$ couples the shot-to-shot energy jitter to the transverse centroid jitter after the TGU, and if a pure drifting space is assumed in the scale of a mid–energy linac after the TGU, the jitter of the beam centroid will be large. However, in a real machine there are quadrupoles as well as accelerating tubes in the linac lattice providing the transverse focus. In our ELEGANT simulation, by imposing 0.04% voltage jitter and 0.09° phase jitter on each S-band accelerating structure, which are the typical S-band parameters of SXFEL, we obtained the jitter of the beam centroid in the horizontal at the exit of L2 (figure 1(b)): $\sigma_{cx} \approx 1.21 \times 10^{-7}$ m. Compared to the rms horizontal beam size at this location, i.e., $\sigma_x \approx 1.13 \times 10^{-4}$ m, the relative variation of the centroid is only <0.1%. The same thing happens in the vertical direction. Therefore, we conclude that the jitter of the beam centroid in the TGU scheme will not be a problem with good transverse matching.

4. Conclusion

In this paper a simple scheme for suppressing the microbunching instability in the linac of a FEL facility via a TGU was proposed and a simulation was carried out to test its validity. The theoretical analysis shows that the TGU was able to suppress the instability as a result of 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 by simulation with the typical parameters of a mid–energy electron linac. As the result, both significant suppression of the instability and good preservation of the horizontal emittance compared to the one without the TGU in the lattice were observed in the simulation. Because the TGU scheme has the advantages of good efficiency, less complexity and better transverse matching, it opens a new way for us to improve the performance of the x-ray FEL, and can be a good device to control the microbunching instability in addition to a laser heater. Finally, as we have described in this paper, the TGU is also able to increase the uncorrelated energy spread of the beam to suppress the microbunching instability. This will be the next topic for us to study in detail.

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