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Applying Transverse Gradient Undulators to Suppression of Microbunching Instability

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Introduction

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 simple and effective scheme is proposed to suppress the microbunching instability by adding two transverse gradient Undulators (TGU) before and after the magnetic bunch compressor. The additional uncorrelated/slice energy spread and the density mixing from the transverse spread brought up by the first TGU results in significant suppression of the instability. Meanwhile, the extra slice energy spread and the transverse emittance can also be effectively recovered by the second TGU. The magnitude of the suppression can be easily controlled by varying the strength of the magnetic fields of the TGUs. Theoretical analysis and numerical simulations demonstrate the capability of the proposed technique in the LINAC of an x-ray free-electron laser facility.

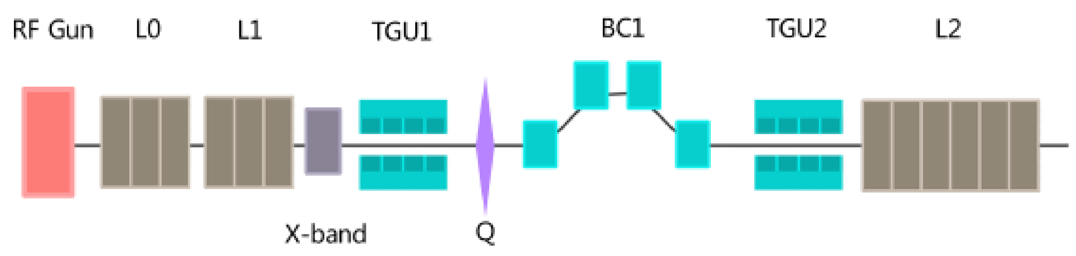


Figure 1. Scheme of suppressing microbunching instability via TGUs

Principles

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 the TGU depends on its transverse coordinate at the entrance of TGU. Without losing generality, assuming Gaussian distribution in the horizontal, after passing through the TGU, the distribution of the beam particles within a longitudinal thin slice becomes

$$f_0(z,x,\delta_\gamma)=\frac{I_0}{(2\pi)^{3/2}\sigma_\gamma\sigma_x\sigma_{x'}}\exp\left(-\frac{x^2}{2\sigma_x^2}\right)\exp\left(-\frac{x'^2}{2\sigma_{x'}^2}\right)\exp\left[-\frac{(\tilde{\delta}_\gamma-h\gamma_0 z-h\gamma_0\tau x-h\gamma_0\tau L_T x'/2)^2}{2\sigma_\gamma^2}\right]$$

For a sufficiently thin beam slice, we make the assumption that all the particles within the slice have the same longitudinal coordinate. It is found in the equation above that the horizontally correlated energy spread is converted into longitudinally uncorrelated energy spread with the energy chirp, 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 same. The energy distribution of the beam at slice z reads

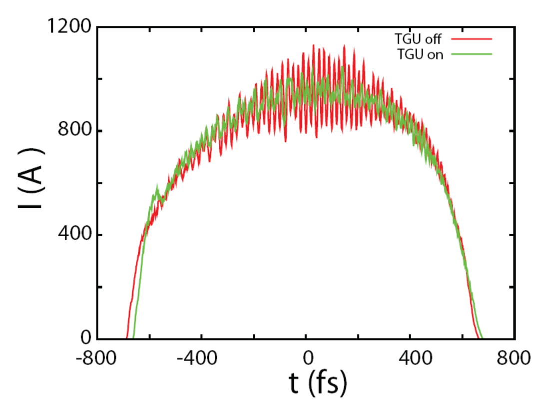
$$f_0(z,\delta_\gamma)=\frac{I_0}{\sqrt{2\pi}\sigma'_\gamma}\exp\left[-\frac{(\delta_\gamma-h\gamma_0 z)^2}{2\sigma'^2_\gamma}\right],\qquad \text{where}\quad \sigma'_\gamma=\sqrt{\sigma_\gamma^2+(h\tau\gamma_0\sigma_x)^2+(h\gamma_0\sigma_{x'}\tau L_T/2)^2}$$

Another important capability of TGU is to introduce the longitudinal mixing from the transverse spread. Including both the extra energy spread shown in the equations above and 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 can be derived

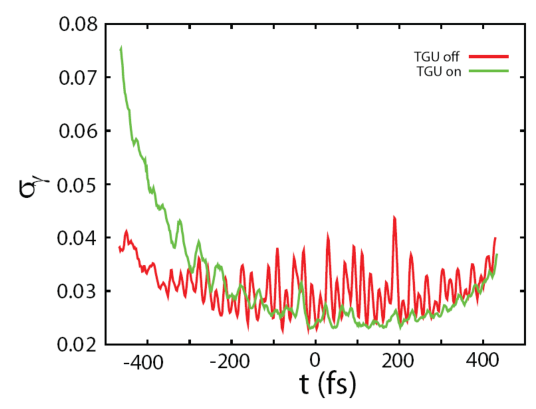
$$G_f\approx G_0\exp\left(-\frac{k^2R_{56}^2\sigma'^2_\gamma}{2\gamma_0^2}\right)\exp\left[-\left(\frac{k^2\tau^2\sigma_x^2}{2}+\frac{k^2\tau^2L_T^2\sigma_{x'}^2}{8}\right)\right]\qquad \text{where}\quad G_0=k|R_{56}|\frac{I_0}{\gamma_0 I_A}\frac{Z(k)}{Z_0}$$

Simulation

To illustrate the problem, the beam with the density (current) modulation of 50 μm in wavelength and 5% in amplitude is employed. The scheme is shown in figure 1. The extra slice energy spread and transverse emittance are recovered by the second TGU, and the quadrupole(s) are used for the matching purpose. The particle tracking code ELEGANT 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.



(a) Longitudinal beam current profile at the exit of TGU2



(b) Slice energy profile of the central part of the beam at the exit of TGU2

Figure 2. Longitudinal beam current profile (upper) and slice energy profile (lower) with TGUs off (red) and on (green) at the exit of the 2nd TGU.

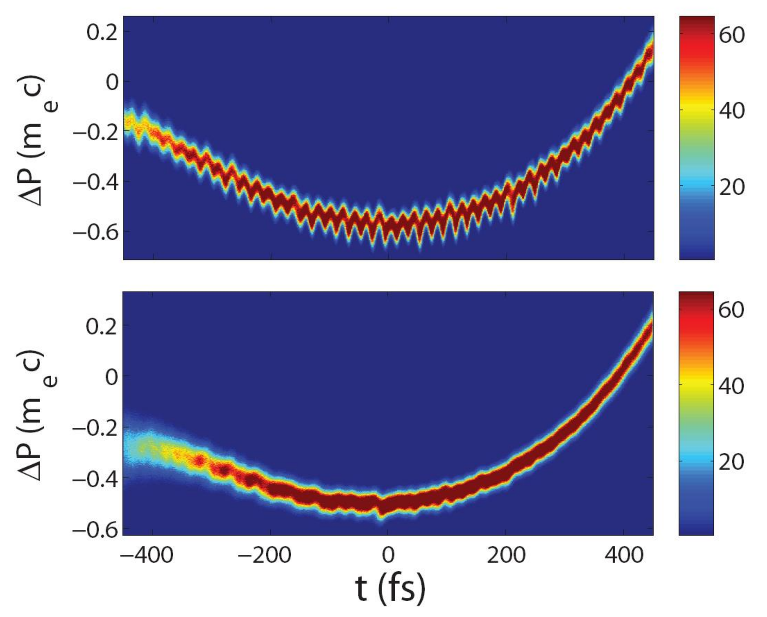


Figure 3. Longitudinal beam phase space with TGUs off (upper) and on (lower) at the exit of the 2nd TGU.

Conclusion

The theoretical analysis shows that the TGU is able to suppress the instability by two factors: the additional slice energy spread and the longitudinal mixing from the transverse spread without changing the direction of the beam propagation. By applying two TGUs symmetrically before and after the bunch compressor, the microbunching instability can be effectively suppressed by those two factors and the beam quality can also be restored very well after all by carefully choosing the TGU parameters. In the simulation, the typical parameters of a mid-energy electron LINAC was employed to demonstrate the feasibility and the efficiency of the TGU scheme, and the result indicates that the scheme we proposed is able to suppress the microbunching instability significantly with the well-preserved transverse emittance and no notable additional jitter and slice energy spread introduced. Moreover, because the TGU scheme does not need external RF power, laser and chicane systems, etc., it has the advantages over the other schemes in terms of high efficiency, less complexity and better jitter tolerance. As a novel method, the TGU scheme opens us a new way to improve the performance of the x-ray free-electron laser, and can be a good candidate for the microbunching instability control in addition to a laser heater.

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