MICROBUNCHING INSTABILITY IN VELOCITY BUNCHING*

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Abstract

Microbunching instability is one of the most challenging threats to FEL performances. The most effective ways to cure the microbunching instability include suppression of the density modulation sources and suppression of the amplification process. In this paper we study the microbunching instability in velocity bunching. Our simulations show that the initial current and energy modulations are suppressed in velocity bunching process, which may be attributed to the strong plasma oscillation and Landau damping from the relatively low beam energy and large relative slice energy spread. A heating effect that may be present in a long solenoid is also preliminarily analyzed.

INTRODUCTION

Magnetic bunch compressors (BC) are generally used to provide high peak current beam to drive the FELs. However, in the bunch compression process the initial current modulations (from drive laser ripples, shot noise, etc) may be amplified and a microbunching instability may develop which degrades the beam quality and FEL performances [1-3]. The process is similar to a high gain klystron-like amplifier where the initial density modulations cause energy modulations due to impedances; the energy modulations are then converted into density modulations in the bunch compression through a dispersion section; after beam's passage through BC, the initial density modulations are amplified and finally the microbunching instability develops [4,5].

Since the FEL output stability is related to that of the rf system through bunch compression process, to enhance the tolerances on amplitude and phase of the linac rf the present FEL projects all use two stage BC to provide high peak current beam. Unfortunately the microbunching gain is very high in the two stage BC configuration so that the microbunching instability may even develop from electron beam shot noise [6,7]. An alternative way to reduce the microbunching gain is to use one stage BC [8], but the tolerance on timing jitter will be more stringent.

Magnetic BC inherently amplifies initial current modulation, because the CSR wake takes a derivative-like feature. That means if there are charge bumps in the beam current distribution, the electrons ahead of them will gain energy while those behind will lose energy. In a dipole, the electrons that gain energy slip back with respect to the reference electron while those that lose energy move forward. This further enhances the bumps. On the contrary, velocity bunching (VB) inherently mitigates the initial current modulation: in a straight section the electrons ahead of the current bump gain energy from longitudinal space charge force and moves forward while those behind lose energy and slips further back. Therefore, it can be anticipated that VB may have a lower microbunching gain and the scheme of a VB plus one BC may be a promising alternative to achieve moderately high peak current (500∼1000 A) beam for driving seeded soft x-ray FEL.

In this paper we study microbunching instability in VB. After introducing the basic principles of VB, we will show the emittance preservation, density and energy modulation propagation in VB. A simple one-step model is used to derive the microbunching gain in VB. Our preliminary studies show that the initial energy modulation didn't effectively convert to density modulation in VB. It might be due to the strong plasma oscillation and the Laudau damping from the relatively large slice energy spread. A heating effect for the beam longitudinal phase space was also preliminarily analyzed.

PRINCIPLES OF VB

VB of electron beams has been observed in photocathode rf gun more than one decade ago [9] and recently it has been proposed to generate high peak current beam in standard separated photoinjectors [10]. The mechanism of VB, as its name suggests, is to generate in the beam velocity difference and rely on the different flight time in the linac to bunch the beam. To be more specific, let's consider a traveling wave accelerating structure for which the longitudinal electric field experienced by an electron is

$$E_z(z,t) = E_0 \sin\phi(z,t)\,. \tag{1}$$

where E_0 is the peak field, $\phi(z,t) = \omega t - kz + \phi_0$, k is the rf wave number and ϕ_0 is the injection phase of the electron. Then the evolution of the phase can be expressed as,

$$\frac{d\phi}{dz} = k\left(\frac{\gamma}{\sqrt{(\gamma^2-1)-1}} - 1\right)\,. \tag{2}$$

The evolution of beam energy can be written as

$$\frac{d\gamma}{dz} = \alpha k \sin\phi\,. \tag{3}$$

where $\alpha = eE_0/kmc^2$ is the dimensionless acceleration gradient. From Eq. (2) and Eq. (3) we get the Hamiltonian of the motion

$$H = \alpha\cos\phi - \gamma + \sqrt{\gamma^2-1}\,. \tag{4}$$

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For simplicity, we first consider a two-particle model. Let's take one electron as the reference particle whose energy and phase are γ_0 and ϕ_0. The other electron has the energy and phase $\gamma_0 + \Delta\gamma_0$ and $\phi_0 + \Delta\phi_0$. The two electrons are injected into an infinitely long traveling wave accelerating structure and at the exit of the structure we can drop the term $\Delta\gamma_\infty/\gamma_\infty$. Keeping only the first order terms we have

$$\Delta\phi_\infty \approx \frac{\sin\phi_0}{\sin\phi_\infty}\Delta\phi_0 - \frac{1}{2\alpha\sin\phi_\infty\gamma_0^2}\Delta\gamma_0\,. \qquad (5)$$

Eq.(5) implies that by properly choosing the injection phase, the electron beam can be compressed in the acceleration process. As compared to magnetic BC, the unique advantage of VB is that there is no CSR effects. However, since VB operates at relatively low energy, more efforts need to be devoted to preserving the emittance as beam current gradually increases in the VB section.

EMITTANCE PRESERVATION IN VB

Since it is the 6-D density of the phase space that determines the FEL performances, in addition to increasing the beam current, the emittance growth should be controlled to an acceptable level as well. For the magnetic BC, it has been demonstrated at LCLS that with proper design of the BC the emittance growth can be controlled to a very low level [11], taking advantage of the relatively high beam energy in the BC. As for VB, because beam energy is relatively low, emittance growth is typically an important concern. In [10], a long solenoid is suggested to preserve the emittance in VB.

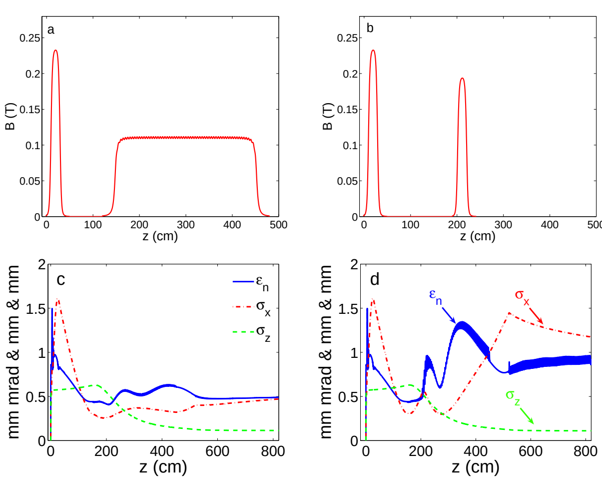

Figure 1: (a) Solenoid field distribution for the ideal case where a long solenoid is used to focus the beam in VB section; (b) Solenoid field distribution for the real case; (c) Emittance, beam size and bunch length evolution in VB for the ideal case; (d) Emittance, beam size and bunch length evolution in VB for the real case.

Here we consider the typical parameters of the LCLS photoinjector beam line where the beam charge is 250 pC and peak rf field is 115 MV/m in the photocathode rf gun. The beam energy is boosted to 135 MeV with two short booster linac: L0A and L0B. We first consider an ideal case where a long solenoid is used to focus the beam in L0A during the VB process. The rf phase of L0A is set to be around the zero crossing to provide a compression factor of 5. The solenoid field distribution and emittance evolution in the VB process for the ideal case are shown in Fig. 1a and Fig. 1c. It follows that with a long solenoid the emittance growth can be controlled within a very small level. At present, in addition to the gun solenoid, there is only a short solenoid at the L0A entrance. For this case the optimized emittance evolution is shown in Fig. 1d where one can see there is a significant increase in emittance, in agreement with the observations in [12] where a significant emittance growth in VB was found when the long solenoid is absent.

PROPAGATION OF DENSITY AND ENERGY MODULATIONS IN VB

Before proceeding to derive the microbunching gain in VB, let's first get some insights from Parmela simulation. We used 200 k macro-particles and simulated the case when there is some current density modulation at the cathode which can be caused by the ripples of the laser. The results are compared to those without density modulation.

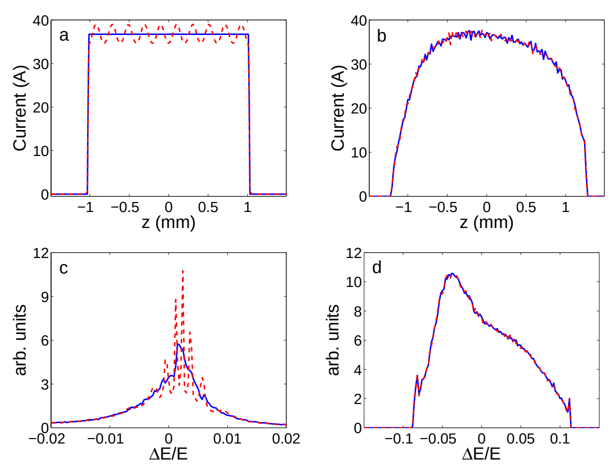

Figure 2: (a) Current distribution at cathode with (red dashed line) and without (blue solid line) laser density modulation; (b) Current distribution at L0A entrance; (c) Energy distribution at L0A entrance; (d) Energy distribution at L0A exit.

We added a 6 % ripple to the current distribution at the cathode, the corresponding beam current distribution at the booster entrance is shown in Fig. 2b. The smearing of the density modulation is mainly from the strong plasma oscillation because beam energy is relatively low. Though the density modulation is suppressed, the plasma oscillation generates considerable energy modulation in the beam, as can be seen in Fig. 2c. The rf phase of L0A is set to be around zero crossing to generate velocity difference which finally results in bunch compression and the beam energy at the exit of L0A is about 20 MeV. Surprisingly, the energy modulation is significantly suppressed at the exit of L0A: it is very close to the case when there is no current density modulation at the cathode.

MICROBUNCHING GAIN IN VB

As shown in last section the initial density modulation at the cathode is significantly smeared at the entrance of the booster entrance due to plasma oscillation and as a result the energy modulation develops. For simplicity we will assume the beam has a flat current distribution at the entrance of the bunching section and a Gaussian energy distribution with a sinusoidal energy modulation,

$$f(s,\delta\gamma) = \frac{I_0}{\sqrt{2\pi}\sigma_\gamma}\exp\left[-\frac{(\delta\gamma - h\gamma_0 s + \Delta\gamma\sin(\tau s))^2}{2\sigma_\gamma^2}\right]. \tag{6}$$

where h is the energy chirp factor, τ and $\Delta\gamma$ are the wave number and amplitude of the energy modulation, respectively. From Eq.(5), we can write the particle position before and after the VB section as,

$$s_f = as_i + b\delta\gamma/\gamma_0\,. \tag{7}$$

where $a = \sin\phi_0/\sin\phi_\infty$ and $b = 1/(2k\alpha\sin\phi_\infty\gamma_0^2)$. Substituting s by $s/a - b\delta\gamma/a\gamma_0$ in Eq.(6) and integrate over $\delta\gamma$ one obtains the current distribution at the exit of the VB section as

$$I(s) \approx CI_0[1 + \rho_{ind}sgn(b)\cos(C\tau s)]\,. \tag{8}$$

where C is the compression factor and ρ_{ind} is the density modulation induced by the energy modulation at the entrance of the VB section,

$$\rho_{ind} = C\tau b\frac{\Delta\gamma}{\gamma_0}\exp(-\frac{1}{2}C^2\tau^2 b^2\frac{\sigma_\gamma^2}{\gamma_0^2})\,. \tag{9}$$

From Eq.(9) it follows that the microbunching gain in VB may be smaller than that in magnetic BC, because γ_0 is much smaller.

A SOLENOID HEATER

When a long solenoid is used to focus the beam in VB process, there may be a heating effect for the longitudinal phase space. The strength of the solenoid is assumed to be $K = B_z/(2B\rho)$, where B_z is the axial magnetic field and $B\rho$ is the magnetic rigidity. Typically we have $K >> 1$ and due to the helical trajectory in the solenoid, at the solenoid exit the longitudinal coordinate for some particle is delayed as

$$s_1 \approx s_0 + R_{56}\delta_0 + T_{511}x_o^2 + T_{533}y_o^2\,. \tag{10}$$

For simplicity we consider a coasting beam with linear energy chirp

$$f(s,\delta\gamma) = \frac{1}{\sqrt{2\pi}\sigma_\gamma}\exp\left[-\frac{(\delta\gamma - h\gamma_0 z)^2}{2\sigma_\gamma^2}\right]. \tag{11}$$

Substituting Eq.(11) into Eq.(10) and the slice energy spread of the beam after the solenoid is found to be

$$\sigma_{\gamma 1} = C\sqrt{4h^2\gamma_0^2T_{511}^2\sigma^4 + \sigma_\gamma^2}\,. \tag{12}$$

where σ is the transverse rms beam size. For typical parameters as those used in Fig. 1 the slice energy spread due to the heating effect from the second order z-x correlation is less than 1 keV which is not sufficient to cure the microbunching instability. In principle one may use a solenoid with strong strength or a large size beam to enhance the heating effect. However, as dictated by Panofsky-Wenzel theorem, this x-dependent longitudinal kick will result in z-dependent transverse kick which will increase the projected emittance. Anyway, this second order z-x correlation should wash out the high frequency modulation for which the modulation wavelength is shorter than $T_{511}\sigma^2$ which may be very helpful to suppress the high frequency microbunching instability developed from shot noise.

CONCLUSIONS

Our simulations show that the initial current and energy modulations are suppressed in velocity bunching process, which may be attributed to the strong plasma oscillation and Landau damping from the relatively low beam energy and large relative slice energy spread. Based on our preliminary study, it seems the scheme of VB plus one stage BC might be a promising candidate for seeded soft x-ray FEL where compression ratio is moderate. More studies are needed to verify the performances of VB plus BC in providing high brightness beam to drive x-ray FEL.

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