Armenian Journal of Physics, 2016, vol. 9, issue 3, pp. 220-224

Electron Bunch Compression and Microbunching in Single-Mode Structure

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Received 04 July 2016

Abstract. The particles energy modulation and the micro-bunching of relativistic electron bunch after bunch interaction with single-mode structure have been studied. It is shown that the bunch particles of non-Gaussian longitudinal shape, interacting with in-structure generated wake fields, cause the energy modulation at the frequency of excited mode. The density modulation in drift space is studied by using the ballistic bunching method. The numerical examples for rectangular and parabolic bunch shapes are presented.

1. Introduction

The generation and acceleration of ultrashort electron bunches is an important issue for generation of coherent radiation in THz and infrared regions, driving the Free-electron lasers and direct applications for ultrafast electron diffraction [1-6]. There are several methods for obtaining sub-ps bunches, e.g. magnetic chicanes are used for high-energy beams shortening [7], velocity and ballistic bunching are for low energy beams [8-11]. For all these methods, one needs to have an energy-modulated beam.

It is well known [12-14] that the relativistic charge, moving along the structure, interacts with the surrounding environment and excites the electromagnetic field known as wakefield. For the charge distribution, the wakefield acts back to bunch particles producing an energy modulation within the bunch by longitudinal wake potential. The form of longitudinal wake potential depends both on the bunch charge longitudinal distribution and on the surrounding structure. Although for Gaussian bunch shape the energy modulation is driven by the bunch head-tail energy exchange, for rectangular and parabolic bunch shapes the energy modulation at high frequency can be obtained.

In this paper, the bunch particles energy modulation in longitudinal wakefields produced during bunch interaction with the single-mode cold plasma is studied. The direct application of the holding integral for bunch rectangular or parabolic shape and point wake potential lead to energy modulation within the bunch at the plasma frequency ω_p. For comparatively low energy bunches the energy modulation causes the velocity modulation and for proper ballistic distance lead to density modulation or microbunching. The bunching and microbunching processes are studied numerically for the bunch energy of 10 MeV. The optimal relations between the bunch shape, plasma density and microbunching distance are analyzed.

2. Energy modulation and compression of Gaussian beams

It is well known that the relativistic charge Q, interacting with surrounding structure, excites the electromagnetic field known as wakefields. The net energy gain (loss) in wakefields of the test charge following behind the driving charge at a distance s, after the driving charge passes the structure of length D, is defined by the point charge wake function given as:

$$w_z(s) = -\frac{1}{Q}\int_0^D E_z(z, t=(z+s)/c)dz\,, \tag{1}$$

where E_z is the longitudinal component of excited electric field and $\boldsymbol{c}$ is the speed of light. As an example of single-mode structure, the interaction of the relativistic charge with infinite cold neutral plasma is considered. The macroscopic dielectric constant of such plasma is given as $\varepsilon = 1-\omega_p^2/\omega^2$, where the plasma frequency is $\omega_p \approx 56.4\cdot 10^3\sqrt{n_e}$ (s^{-1}) with n_e being the plasma electron density. The wake function of the relativistic point-charge, passing the cold neutral plasma, is given by [15, 16]:

$$E_z = -2QH(s)K_{loss}\cos(k_p s), \tag{2}$$

where $H(s)$ is the Heaviside step function, $k_p = \omega_p / c$ is the wave number, K_{loss} is the longitudinal loss factor that defines the energy loss of the driving charge in plasma per unit length $U_0 = Q^2 K_{loss}$. The longitudinal wake potential for the bunch with charge distribution $\lambda(s)$ could be obtained using the convolution integral:

$$W_z(s) = \int_{-\infty}^{s} w_z(s - s')\lambda(s')ds' \tag{3}$$

The numerical simulations of bunch compression and microbunching processes have been performed for the driving bunch charge of 100 pC and structure of $K_{loss} = 90kV/m/pC$ loss factor.

Fig. 1 presents the wake potential of the Gaussian charge distribution with 100 μm rms bunch length in 20 cm plasma channel with the plasma frequency $f_p = \omega_p / 2\pi = 1.43\,THz$ (wavelength $\lambda_p = 210\mu m$).

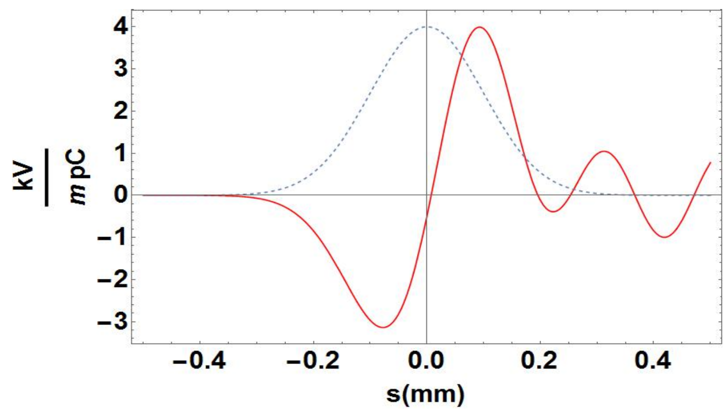

Fig. 1 Gaussian bunch wake potential.

According to Fig. 1, the wake potential is retarding at the bunch head and accelerating at the bunch tail. This energy modulation can drive to the bunch length shortening in drift space for the low energy electrons. To evaluate the bunch compression we define the energy of i-th particle in the bunch with s_i longitudinal coordinate as:

$$E_f(s_i) = E_0 + eQW_z(s_i)L, \tag{4}$$

where E_0 is the initial energy of particles and $eQW_z(s_i)L$ is an energy change of i-th particle due to the wakefield. Here Q is the total charge of the bunch, L is the length that the bunch passes in the structure, and it is assumed that the initial energy of each particle in the bunch is the same.

The bunch passes the structure being followed by a drift space section, where charge density modulations occur due to energy modulations. The coordinate of i-th particle after passing l_{drift} distance in a drift space is

$$s_{1i} = s_{0i} + \Delta s_i = s_{0i} - l_{drift}\left(\frac{\beta_1(s_{0i})}{\beta_0} - 1\right), \tag{5}$$

where s_{0i} is the initial coordinate of *i*-th particle, $\beta_0 = v/c$ is the bunch initial velocity, $\beta_1(s_{0i})$ is the velocity of *i*-th particle after passing the structure.

Numerical simulations are used for observing wakefield effects on various line charge distributions. The bunch is presented as an ensemble of N_{tot} particles that experience the energy deviations in longitudinal wakefield as shown in Fig.1 for beam with Gaussian distribution. For the simulations $N_{tot} = 10^6$ particles have been used. The compressed bunch shape after traveling a distance of 3.5 m is shown in Fig. 2. The dashed line presents the initial Gaussian bunch distribution. The rms length of the distribution central part that contains 70 % of the particles is about 15 μm. The rms length compression of the Gaussian bunch central part (70 % of particles) versus the bunch travel distance in free space is shown in Fig. 3. The maximum bunch compression is reached at the distance of about 4 m (bunch rms length $\sim 12 \mu m$) after which the debunching process starts.

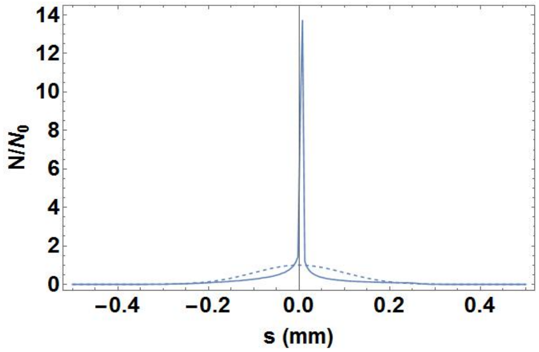

Fig. 2 Line charge distribution at the distance 3.5 m.

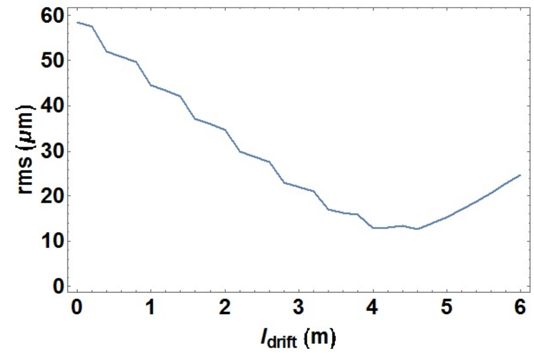

Fig. 3 The Gaussian bunch longitudinal compression versus the drift distance.

3. Energy modulation and microbunching of non-Gaussian beams

For the rectangular uniform charge distribution, the single-mode wake potential produces the particles energy modulation at the excited mode wavelength. Fig. 4 shows the energy modulation in wakefields within the rectangular bunch of 2 mm total length (rms bunch length is about 0.58 mm) after bunch passing the structure of 0.3 m length. The excited mode wavelength is taken 0.6 mm (~0.5 THz).

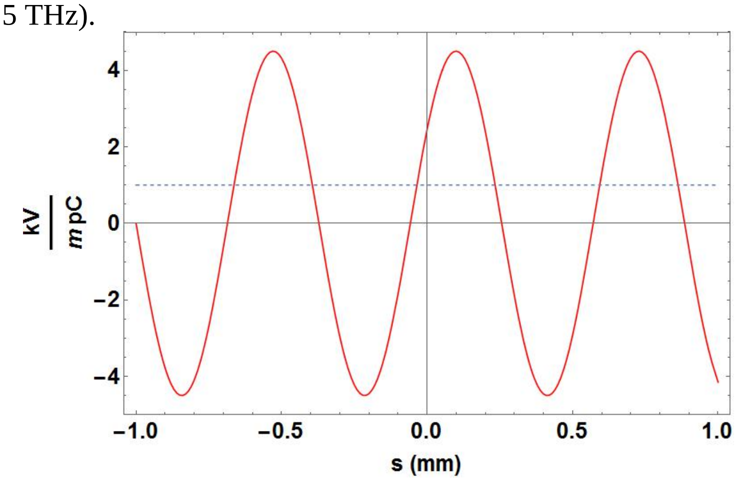

Fig. 4 Uniform bunch wake potential.

The energy modulation at the excited wakefield mode frequency leads to the charge density modulation as the beam travels in free space. Fig. 5 shows the density modulation at 1.5 m and 3.5 m distances. As is seen, the density modulation leads to microbunching. In the presented example at the distance of 3.5 m the initial rectangular bunch is transformed into three microbunches with 40 μm full width at half maximum (FWHM).

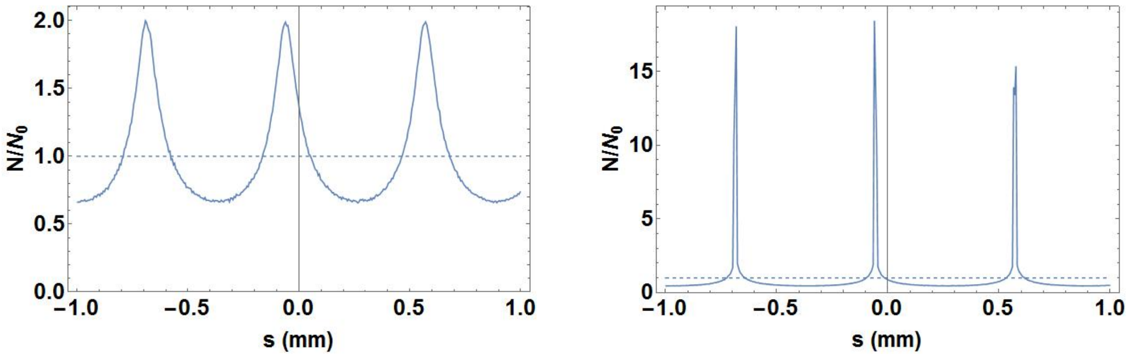

Fig. 5 Line charge distribution after passing l_{drift} distance in a drift space:

$l_{drift} = 1.5m$ (left), $l_{drift} = 3.5m$ (right).

The wake potential for parabolic charge distribution of 2 mm full length is shown in Fig. 6. The dashed line represents the bunch shape. The excited mode wavelength is 0.6 mm and the structure length is 1 m. As it is seen, the particles energy modulation is observed with linear ramp of the average energy deviation.

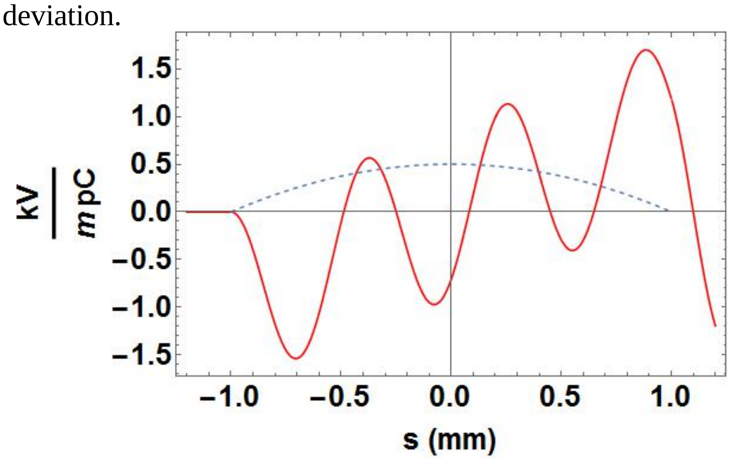

Fig. 6 Parabolic bunch wake potential.

Fig. 7 shows the microbunching of the initial beam at 3 m and 5 m distances.

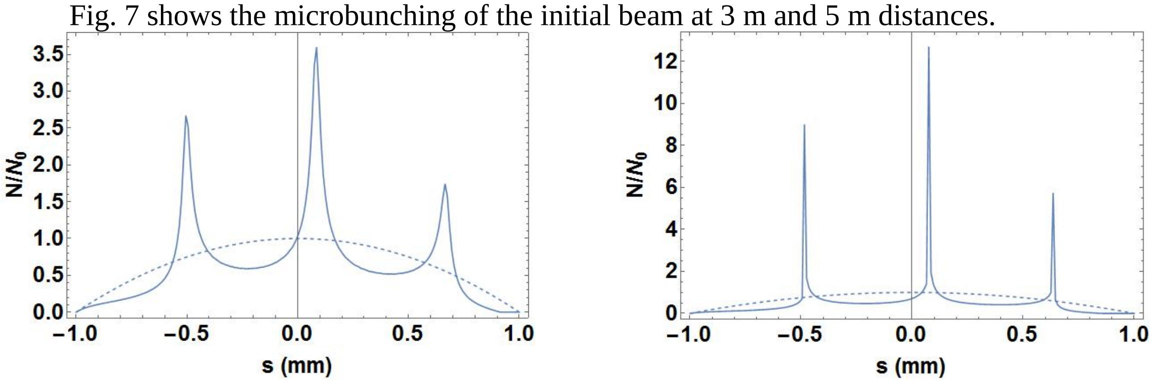

Fig. 7 Line charge distribution after passing l_{drift} distance in a drift space:

$l_{drift} = 3m$ (left), $l_{drift} = 5m$ (right).

The bunch is transformed into three micro-bunches. The best bunching is observed on a drift space of 5 m length, where micro-bunches with 20 μm length (FWHM) are formed.

Conclusions

The compression and density modulation of relativistic electron bunches via ballistic method have been studied for the beam interaction with single-mode structure. It is shown, that this interaction leads to compression of the Gaussian bunch. For the uniform or parabolic bunches the microbunching process can be obtained. The Gaussian bunch with 100 μm rms length and 100 pC charge can be compressed by factor of 10. Uniform bunch with 2 mm total length and 100 pC charge can be splitted into several micro-bunches with 40 μm length (FWHM) and 14 pC charge. Parabolic bunch with 2 mm full length and 100 pC charge forms several micro-bunches of 20 μm full width and 10 pC charges.

Acknowledgments

I wish to thank Prof. V. Tsakanov, Dr. M. Ivanyan and Dr. A. Grigoryan for their enlightening advices and comments.

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