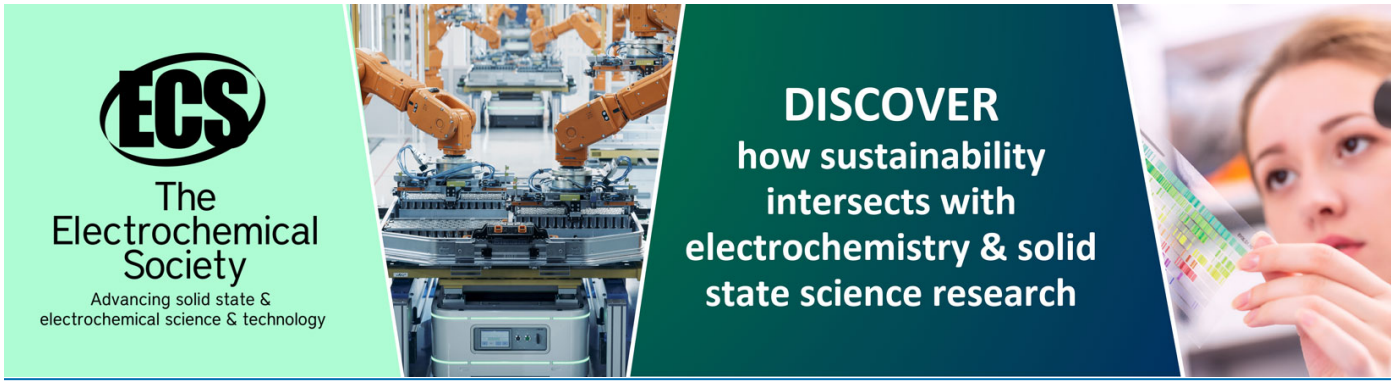
Self-compression of dense photo-injector electron bunches



Self-compression of dense photo-injector electron bunches

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Abstract. Several different mechanisms of compression of dense electron bunches in self fields are described. It is shown that the spontaneous radiation from a short (shorter than the radiation wavelength) electron bunch can result in a significant axial compression of the bunch under effect of the rf field of the radiated wave. This radiative self-compression can be provided in regimes of both cyclotron and undulator emission. Self-compression in the case of the "negative-mass" regime of the electron motion in an undulator of a special type is also described.

1. Introduction

Modern photo-injector ensure formation of dense electron bunches of picosecond durations with charges of up to 1 nC (that corresponds to kA currents), and with particles energy at the level of 3-7 MeV [1-5]. Obtaining ultra-short (shorter than 1 picosecond) dense electron bunches is a task demanded by a number of important physical applications, including modern high-gradient plasma accelerators, the physicochemical studies of ultrafast processes, free electrons laser and the generation of powerful coherent terahertz radiation, based on the spontaneous emission (this type of radiation process is realized, when the effective phase size of the electron bunch with respect to the radiated wave is small enough ($< 2\pi$), so that the wave packets emitted by each of the electrons add up basically in phase).

The aim of this work is the study of physical mechanisms of compressing dense moderately relativistic electron bunches by self electromagnetic fields (quasi-static Coulomb electric fields and radiation fields). Several different mechanisms of self-compression are described. It is shown that the spontaneous radiation from a short electron bunch can result in a significant axial compression of the bunch under effect of the rf field of the radiated wave. This radiative self-compression can be provided in regimes of both cyclotron and undulator emission. Self-compression in the case of the "negative-mass" regime of the electron motion in an undulator of a special type (a helical undulator immersed in a axial magnetic field) is also described.

2. Mechanisms of self-compression

One of main problems in providing the powerful spontaneous emission from a short electeron bunch is a strong Coulomb repulsion leading to an increase of the axial bunch size [6]. Indeed, for the process of the spontaneous emission to take place, the effective phase size of the electron bunch with respect to the radiated wave should be small enough ($< 2\pi$) (Fig 1), so that the wave packets emitted by each of the electrons add up mostly in phase. If the radiation mechanism is based on the longitudinal electron bunching (either ubitron or cherenkov masers), then the phase size is just proportional to the length of the bunch. Therefore, axial expansion of the bunch leads to an increase in the bunch phase

size with respect to the radiated wave and, consequently, impede the radiation.We propose several methods of electron bunches compression by self fields.

2.1. Super-radiative self-compression

We consider the undulator radiation from a short bunch moving along a helical trajectory in an undulator (Fig. 1 a). The wavelength of the radiated wave is longer than the axial beam length (Fig. 1 b), so that the radiation has the spontaneous coherent character. The compression is realized when the group velocity of the radiated wave is close to the axial electron velocity, so that the radiated rf wave does not leave the region of the electron bunch (super-radiative regime) [7,8].

The axial compression of the bunch appears, when the bunch shifts to the "proper" wave phase, so that its front is placed in the maximum of the decelerating phase of the radiated rf wave, whereas the tail is close to the zero wave field (Fig. 1, a). The "proper" phase of the radiated rf wave is settled due to two factors, namely, (i) super-radiative character of the emission and (ii) a short length of the bunch. This type of compression is described in details in the works [9,10]. This regime was simulated using 3D PIC-code KARAT. The maximal compression for the bunch with typical for modern photo-injector parameters (total charge 0.1 nC, initial length 0.9mm, radius 1mm, and particles energy 3MeV) is provided at times 5-8 ns, which corresponds to a length of 1.5-2.4 m. It is interesting that after this point we do not observe a fast destruction of the compressed bunch, so that a close-to-stable state of the bunch is maintained at a distance of several meters [9].

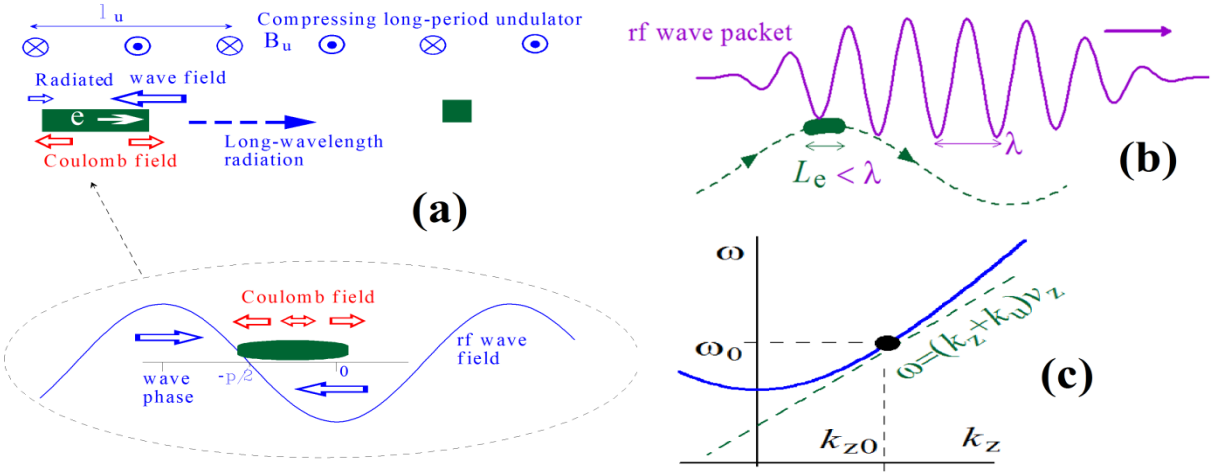

Figure 1. (a): the radiation in the undulator leads to the axial compression of the electron bunch and to the spontaneous excitation of the THz wave, the bunch phase according to the case of compression; (b): the spontaneous radiation: length of the bunch is small respect to the wave; (c): the group resonance regime: the electron velocity close to the group velocity of radiated wave.

In the letter [9] we propose the compression under effect of radiation of a long-wavelength wave as a mechanism for control the axial size of the bunch. In fact, we propose a two-wave rf source based on spontaneous undulator radiation (Fig. 2,a). The use of an auxiliary undulator with a relatively long period leads to emission of a wave with a wavelength longer than the axial bunch size. In certain conditions, this auxiliary wave possesses the "proper" phase with respect to the bunch, namely, the bunch front is placed in the maximum of the decelerating phase of this wave, whereas the bunch tail is close to the zero field. In this situation, the auxiliary long-wavelength wave provides a significant compression of the bunch down to a "terahertz" length, which results in emission of a THz wave in the main short-period undulator.

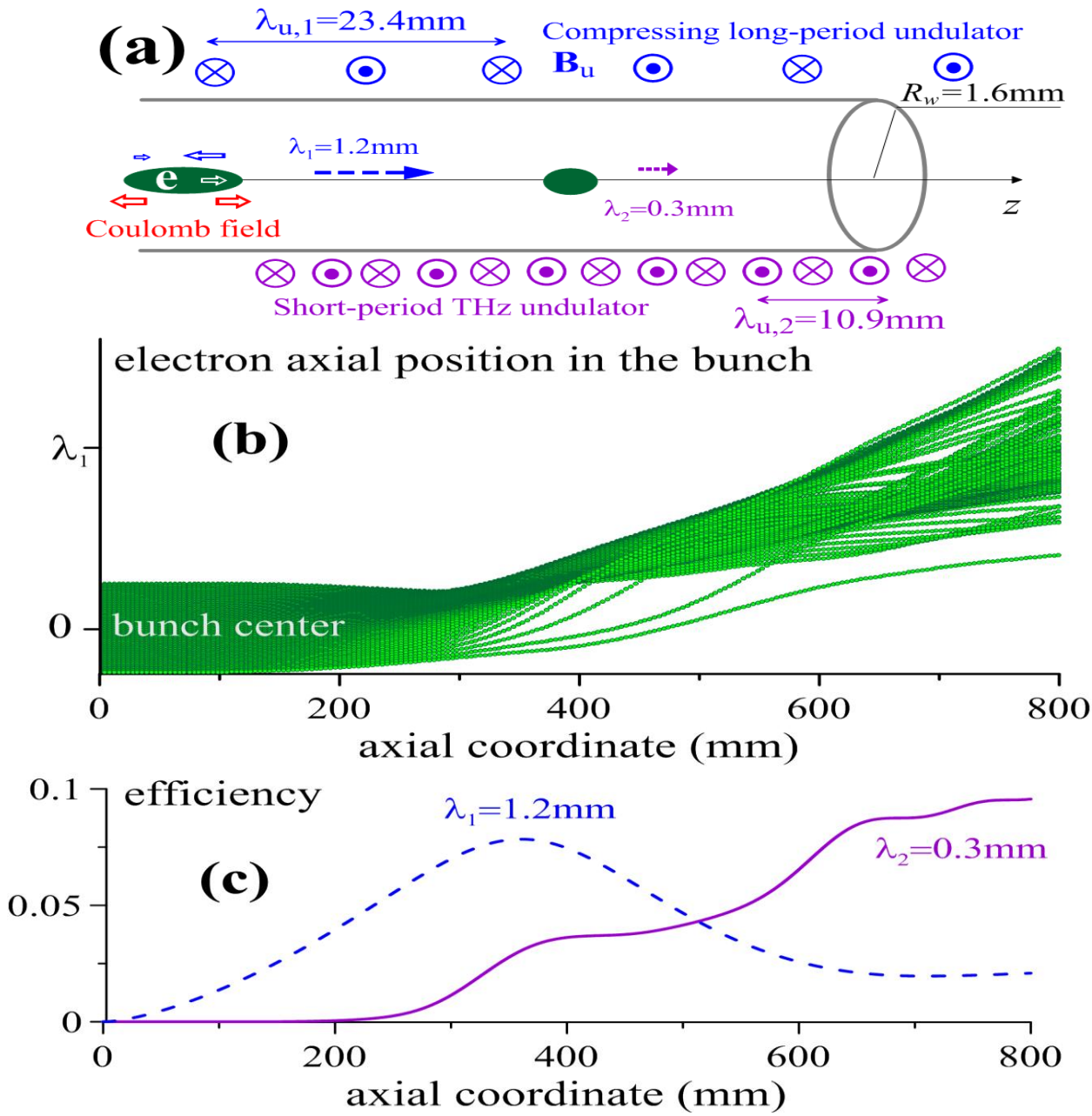

Figure 2. (a): Bicolor rf source: spontaneous radiation of long-wavelength wave leads to the compression of the electron bunch and to the spontaneous excitation of the THz wave. (b) Dynamics of the electrons axial positions in the bunch in the electron-wave interaction process. (c) efficiencies of excitation of the two waves.

Figure 2 illustrates numerical simulation for the simplest model described above. The initial bunch size is equal to $\lambda_1/2 = 0.6$mm, the transverse size is $2R = 2$mm, the total bunch charge is 0.1nC, and the energy is 3MeV. At the initial stage of the radiation process, the bunch emits a long-wavelength wave ($\lambda_1 = 1.2$mm) due to oscillations in the compressing auxiliary undulator (having a period of 23mm and an undulator factor of $K_1 = 0.8$). Due to self-compression of the bunch in the field of the long-wavelength wave (fig. 2, b), the effective axial bunch size is reduced down to a value smaller than the wavelength of the second wave, $\lambda_2 = 0.3$ mm. The compressed bunch is able to emit this 1 THz wave due to oscillations in the second undulator (with a period of 11mm and $K_2 = 0.9$).

As a result, the efficiency of excitation of the 1THz wave in the spontaneous regime achieves 10 % at the interaction length which is as short as several tens cm.

2.2. Cyclotron compression

This type of compression can take place when a short bunch moves along a helical trajectory in a waveguide immersed in the axial magnetic field (Fig. 3, a). If the wave group velocity of the radiated wave is slightly smaller than the longitudinal velocity of electrons, the cyclotron self-compression appears. In this case, the center of a bunch in the phase space is close to the stable "zero" phase of the radiated wave (Fig. 3, b). The change of the "proper" bunch phase in comparison with the undulator radiation case is caused by different signs of energy and velocity changes for the electron-wave interaction [11].

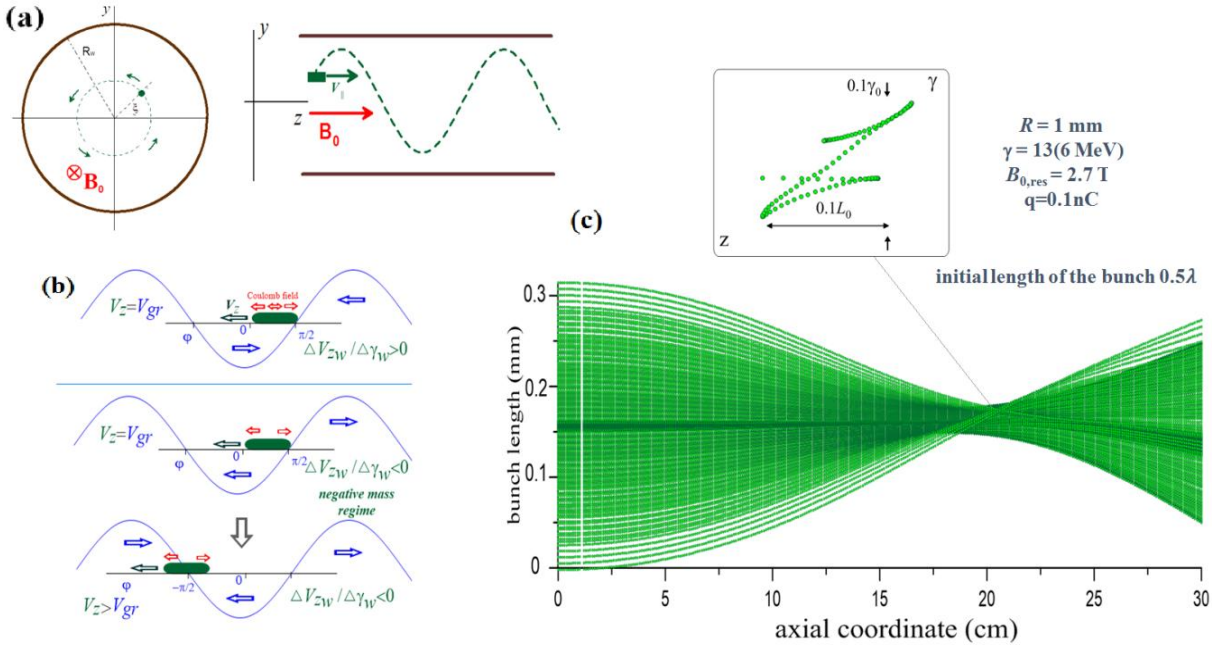

Figure 3. (a): cross section of the cavity, the longitudinal section of the cavity; (b): bunch phase with respect to the radiated wave. (c): results of numerical simulation of the compression process.

In cyclotron resonance masers the bunch is compressed to its center placed close to the "zero" wave phase (Fig. 3 c). Numerical simulations show the possibility to decrease the bunch length (particles energy 6 MeV, total charge in the bunch 0.1 nC, initial bunch length 0.3 mm, bunch radius 1mm) by a factor of 5 at lengths of several tens cm. The initial bunch length accords to the half of the radiated wave length 0.6 mm, that accords to the resonant magnetic field of 2.6 T.

2.3. Self-compression in the «negative mass» regime

It seems natural to benefit from the gigantic coulomb field inside an electron bunch. It is possible in the so called "negative mass" of the electron motion [12-14]. This regime is realized, when the electron moves in a combination of periodic undulator field and relatively strong homogeneous longitudinal magnetic field, and the cyclotron frequency corresponding to the longitudinal field is slightly higher than the undulator bounce-frequency of the particle (Fig. 4). Then increase of the electron energy will lead to a reduction of its cyclotron frequency, since the latter is inversely proportional to the relativistic mass-factor of the particle. The electron approaches the undulator-cyclotron resonance, which is accompanied by a resonant increase in its transverse velocity. When it is close enough to the resonance, such a transverse velocity pumping occurs due to decrease of the

longitudinal electron velocity. Thus, increasing the energy of the particle causes it to slow down in the longitudinal direction, which can be regarded as a consequence of its effective mass being negative. With regard to the dynamics of the electron bunch, it means that the Coulomb force leads not to the repulsion but to the attraction of electrons. A similar effect is well known in cyclotron accelerators [15-17] and cyclotron resonance masers [18-20].

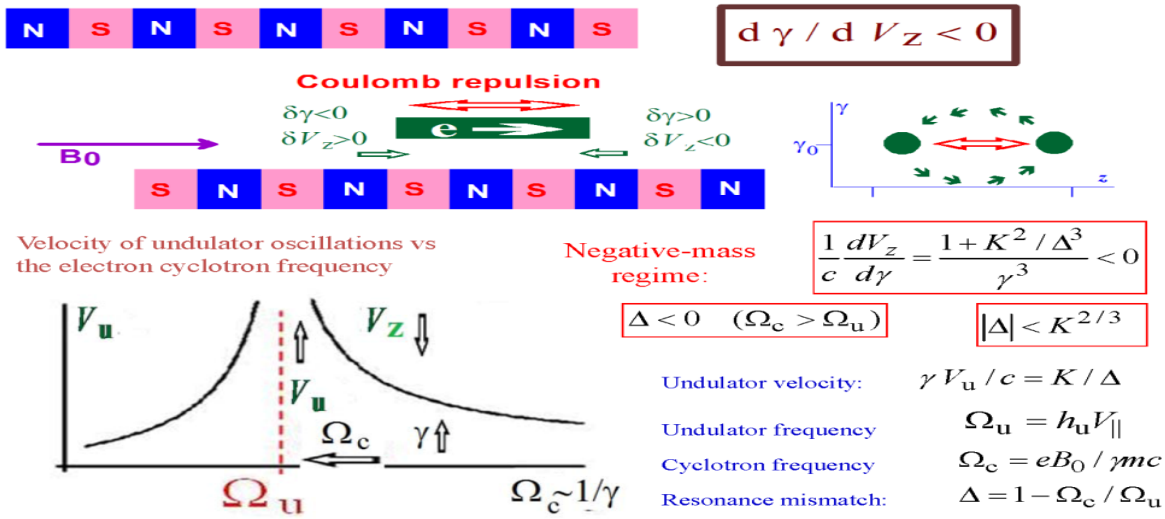

Figure 4. Negative mass regime is realized if the frequency of electron cyclotron rotation slightly greater than the frequency of bounce oscillation in the undulator Ω_u.

Obviously, the coulomb interaction leads to the decrease of the bunch length in such regime. The compression is improved by the radiation in the "proper" phase. The "proper" place of the bunch is the same as in the case of the cyclotron compression due to the relation between energy and velocity changes. The results of the numerical simulations show that the improvement is significant (Fig. 5, b). The bunch length in the point of the compression maximum is 0.1 of the initial length in the case of the coulomb compression, the compression by the coulomb field and the radiated wave field simultaneously provides the bunch length decrease by factor ~200 at the lengths according to the several tens undulator periods.

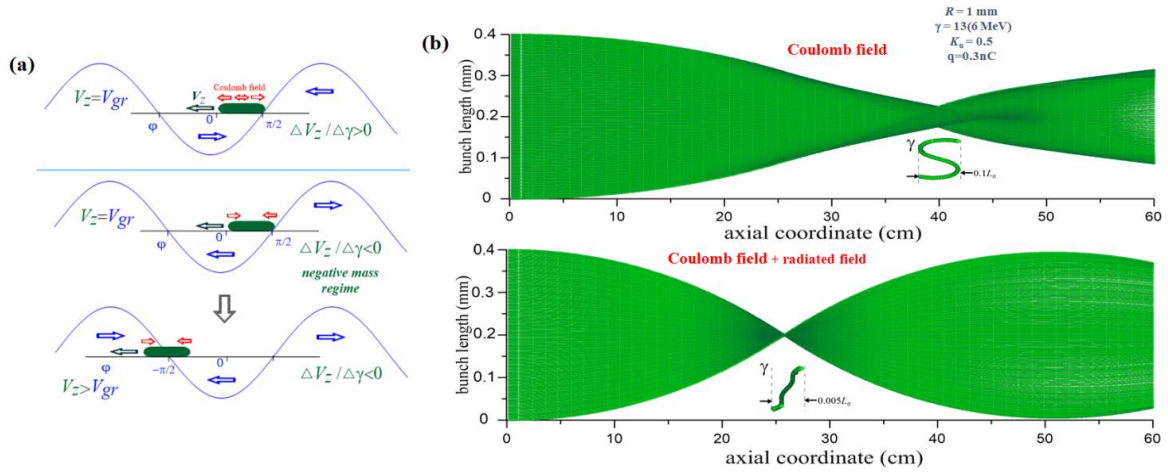

Figure 5. (a): The bunch phase with respect to the wave in the negative-mass regime. (b): The results of numerical simulation (the electrons initial energy 6 MeV ($\gamma_0 = 13$), total charge of the bunch 0.3 nC, the initial length 0.4 mm, the bunch radius 1 mm) for two cases: coulomb field only on the top and coulomb field + radiated wave field (λ= 0.8 mm) on the bottom. The undulator parameter is 0.5 and the period is 1 cm.

3. Conclusion

We have described main mechanisms of self-compression. The results of numerical simulation demonstrate the possibility of making ultra-short dense bunches (with lengths ~0.1 mm and charges ~0.1 nC) The bunch with length ~0.1 mm is "ready for radiation" of a THz range-wave in the regime of spontaneous emission. Obviously, it is possible to use these methods for the realization THz source based on the spontaneous coherent radiation.

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